FM SIGNAL DETECTION THROUGH AM RECEIVER TIME-DERIVATIVE TECHNIQUES

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by

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ABSTRACT

This paper is concerned with the implementation of detection of commercial radio FM and AM signals by a single detection device. Detection of FM signals on an AM radio by time-derivative techniques (slope detection) and its application to commercial FM/AM radios will be developed. Subjects to be discussed include current FM (radio) detection techniques, matching networks, frequency conversion (mixer), filtering of the difference frequency, laboratory results (detuning of the I.F. transformer) and conclusions.

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I. INTRODUCTION

Detection of a frequency-modulated (FM) signal can be performed by any number of devices. Among the more popular devices used in commercial receivers are the discriminator (frequency or phase) and ratio type detectors. However, detection is not limited to these devices. In fact, any device whose output is the time-derivative of the input will perform an FM-to-AM conversion and therefore can be used to detect FM [1]. After FM to FM-AM conversion is made, detection can be performed by conventional AM detection techniques (envelope detector). This is known as slope detection or more descriptively called time-derivative detection.

Since the I.F. stage of an amplitude-modulated (AM) signal commercial receiver has a response curve similar to that shown in Figure 1, it meets the time-derivative requirements for slope detection and can be used for FM to AM conversion. Therefore, if the FM signal can be made to correspond in frequency to the slope of Figure 1, the AM receiver I.F. and detection circuitry can be used as an FM detector.

This process of detection is not new to the communications field. During the late 1940's, television sound systems were changing from AM to FM type transmissions [2]. Rather than installing new circuitry in existing television sets, a slope detection method for FM detection was applied. By detuning the I.F. transformer of

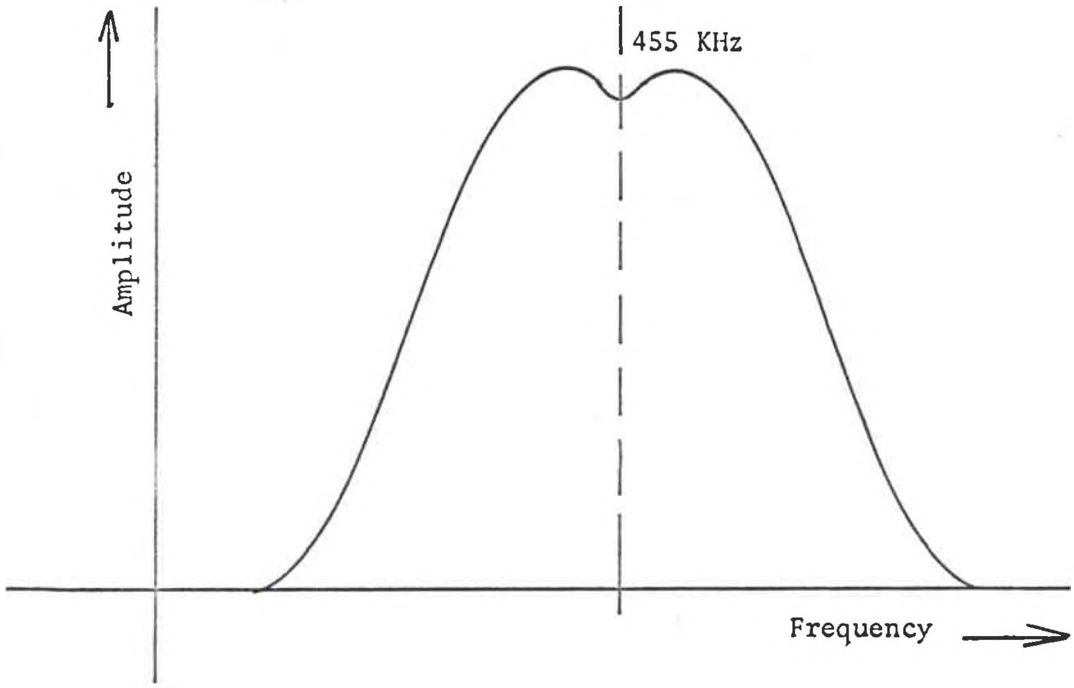


Figure 1 - Typical Commercial AM Radio I.F. Response Curve

the previously AM circuitry to obtain as linear a slope as possible, FM detection was accomplished. This is pictorially displayed in Figure 2.

The effort behind this paper is to apply slope detection techniques to the detection of FM commercial radio transmissions on a commercial AM receiver. If such a transition can be successfully performed (with good fidelity), FM/AM receivers can be reduced in their complexity. The chapters that follow will show the development of the technique to be used in the laboratory to determine the desired

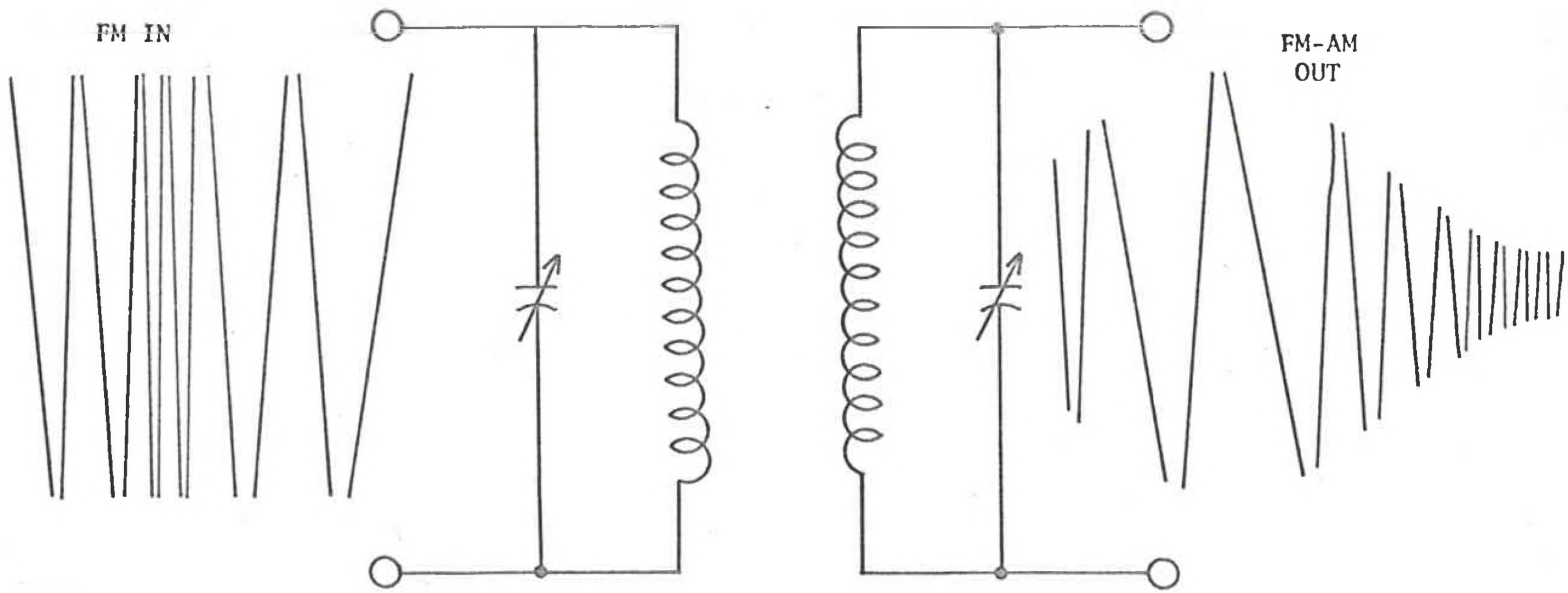


Figure 2 - FM to FM-AM Conversion

results. This development will include the approach to be taken in this paper, a review and comparison of the more popular commercial FM receiver detection techniques, the integration problem (matching network, mixer, and difference filter), along with laboratory results and conclusions.

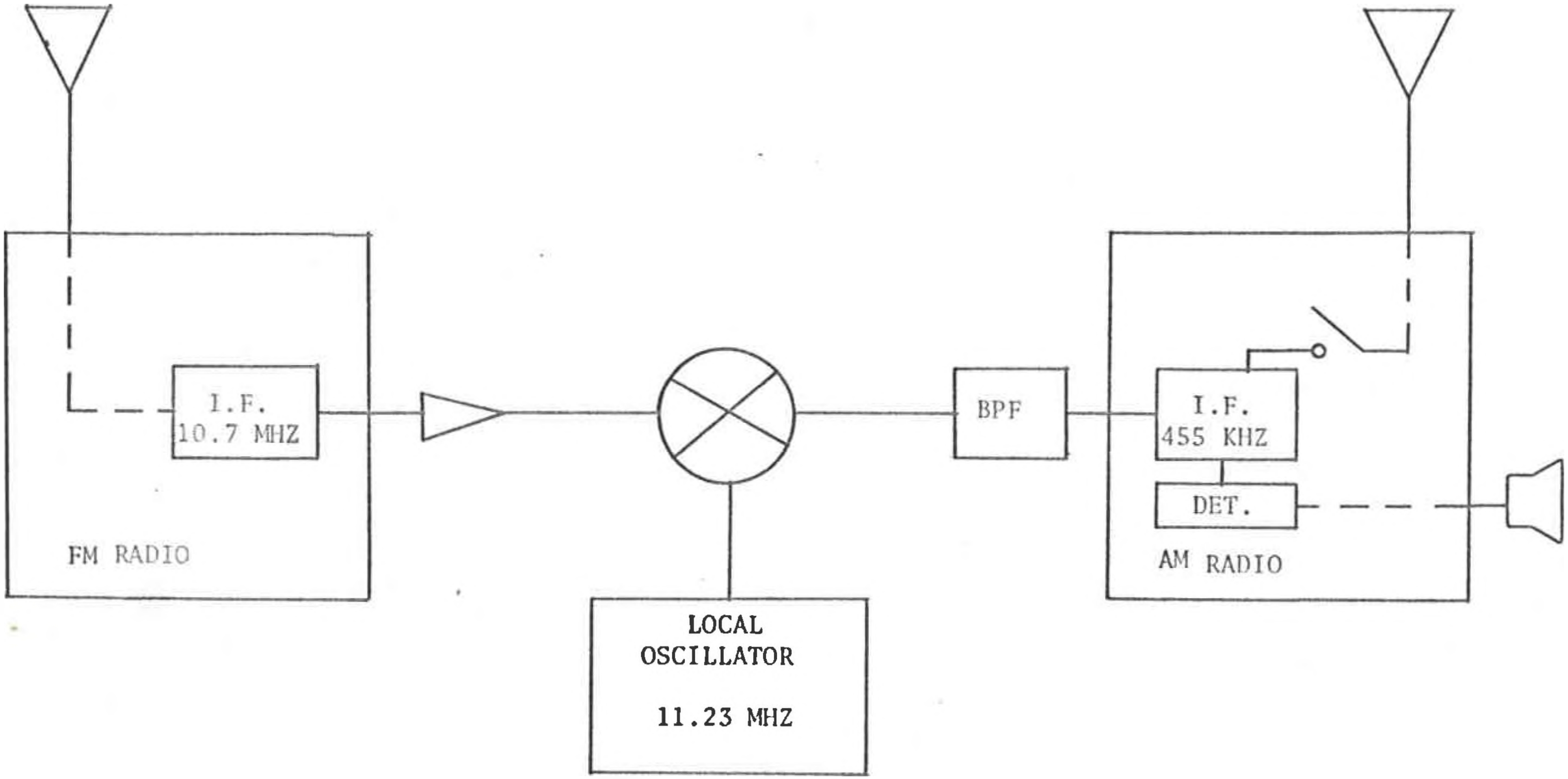
II. APPROACH: THE INTEGRATION PROBLEM

In considering detection of a commercial FM radio signal on a commercial AM radio, many problems of integration arise. Initially, the problem is that of acceptance of the FM frequency band (88 MHz to 108 MHz) by the AM radio (550 KHz to 1600 KHz) circuitry. The problem also arises of individual station bandwidths. According to Federal Communication Commission (F.C.C.) regulations, FM radio stations are permitted a bandwidth of ±75 KHz, while AM radio stations are permitted a bandwidth of ±10 KHz. Again, the problem of AM receiver circuitry will not allow acceptance of FM transmitted signals without distortion due to band limitation.

Signal strength contributes directly to the integration problem also. If the signal, as tapped from the FM radio, is not at the proper voltage level at the point of insertion into the AM radio, detection will be nil.

The approach that will be used in solving the integration problem is depected in block diagram form in Figure 3. The following discussions are with reference to this diagram.

(a) FM Radio. The FM signal source is a commercial FM radio with an operating band between 88 MHz and 108 MHz. Heterodyning



(a) (b) (c) (d) (e)

Figure 3 - System Integration

principles will be utilized to obtain a signal whose frequency will be applicable to a commercial AM radio I.F. response curve slope as described in Chapter I. This requires that the signal be centered at approximately 455 KHz ±75 KHz (approximately 380 KHz if detection will be performed on the positive slope of the response curve; approximately 530 KHz if detection will be performed on the negative slope of the response curve). To simplify matters, instead of "tracing" the local oscillator with the tuning capacitor of the FM radio, a constant-amplitude signal generator (set at one frequency) will be used. This can be done only if the output of the FM radio (at the point where the signal will be tapped) is constant in frequency (with the exception of the ±75 KHz deviation). Therefore, the point chosen for FM signal tapping was the final I.F. stage where the signal, regardless of particular station frequency, is always 10.7 MHz ±75 KHz.

(b) Amplifier. A linear amplifier is used to amplify the low-level signal from the FM radio output.

(c) Mixer - Local Oscillator. The local oscillator is fixed at a frequency of 11.23 MHz. When introduced into the mixer with the FM signal (10.7 MHz ±75 KHz), sum and difference frequencies are produced. The difference frequency will be 530 KHz with a deviation of ±75 KHz directly proportional to the FM signal. Rationale for this selection (negative response curve slope detection) will be discussed in Chapter VI.

(d) Bandpass Filter. A bandpass filter is required for acceptance of the 530 KHz ±75 KHz difference frequency from the mixer. It provides attenuation of the sum frequency as well as the two original frequencies from the mixer and harmonics that may be present.

(e) AM Radio. The processed FM signal is now ready for insertion into the AM radio. Insertion is made at the secondary coil of the I.F. transformer as shown in Figure 4. FM to AM conversion is performed at this point. The signal is now ready for conventional AM detection devices. The tuned station on the FM radio should then be audible at the output (speaker) of the AM radio. It is anticipated that for best reception and least distortion, the I.F. transformer of the AM radio will require detuning.

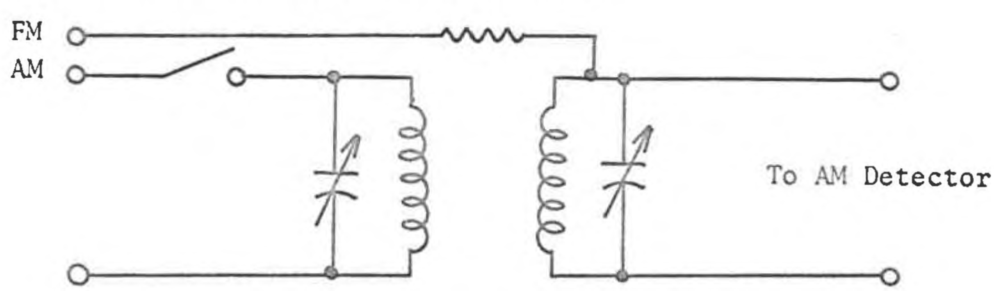


Figure 4 - FM Insertion Point To AM Radio

Throughout the transfer networks from FM radio to AM radio, "T" resistive type matching networks were employed to provide maximum signal transfer through the predominately passive networks.

III. COMPARISON OF FM DETECTION TECHNIQUES

It is necessary at this point to make a comparison of some of the most commonly accepted techniques for FM detection against the proposed slope detection technique herein. This comparison, along with laboratory data on slope detection, will form the basis for the conclusions of this paper. It is not the intent of this paper to perform a detailed analysis of each type of FM detector, but rather to consider the basic techniques of each detector and compare these with the proposed slope detection techniques.

Of the methods of FM detection available, the most basic are the discriminator (frequency or phase) detector and the ratio detector. The following paragraphs are a description of the technique of FM detection applied by each of these detectors [3].

Discriminator Detectors

Frequency discriminators are the most basic of FM detectors. The double-tuned (Crosby) discriminator shown in Figure 5 is a frequency discriminator [3]. The technique used for detection of an FM signal in this circuit is as follows:

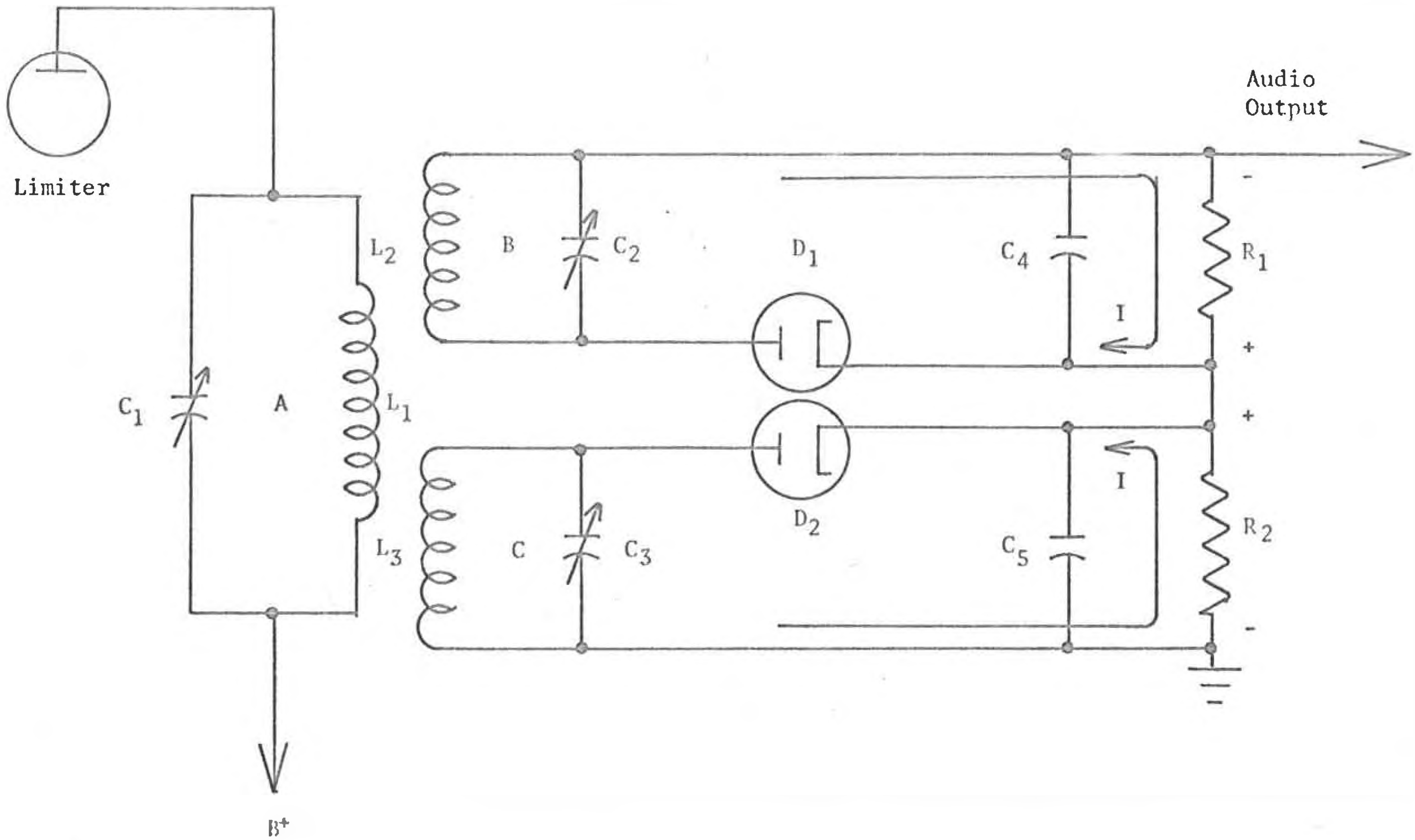


Figure 5 - Frequency Discriminator

a. Incoming FM signals at an I.F. frequency of 10.7 MHz are amplitude limited through the limiter tube to eliminate any AM that may be "riding" on the FM signal.

b. Tank circuit "A" is tuned to 10.7 MHz with a wide enough bandwidth so as not to introduce amplitude variations of the FM signal at this point. The output of this tank circuit is symbolically shown in Figure 6.

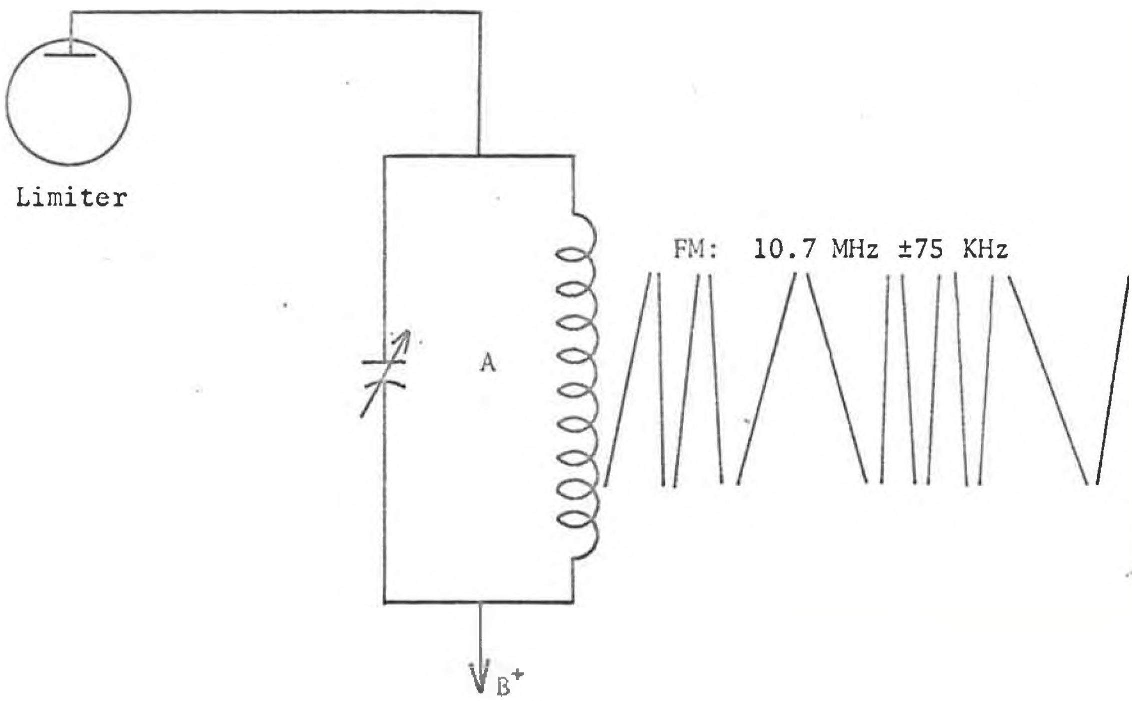
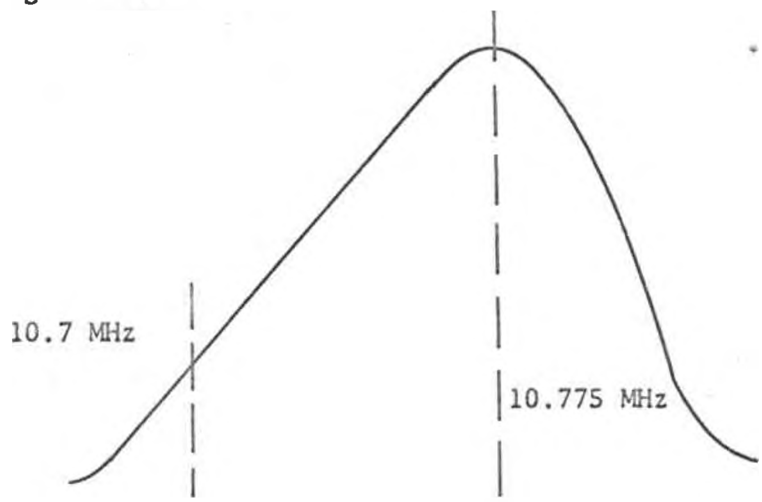
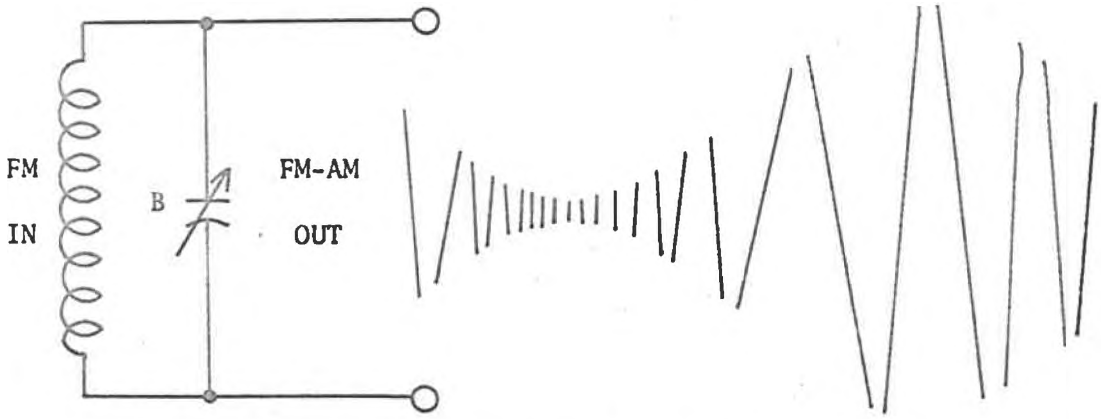


Figure 6 - Tank Circuit "A" Output

c. Tank circuit "B" is tuned above 10.7 MHz so as to position the response curve slope at those frequencies +75 KHz above 10.7 MHz as shown in Figure 7a. The output is therefore an FM-AM signal as shown in Figure 7b.



a) Tank Circuit "B" Response Curve



b) Input-Output of Tank Circuit "B"

Figure 7 - Tank Circuit "B" Characteristics

d. Tank circuit "C" is tuned below 10.7 MHz so as to position the response curve slope at those frequencies -75 KHz below 10.7 MHz.

The resultant is an FM to FM-AM conversion of the signal similar to that of tank circuit "B".

e. The remainder of the circuit is simply two envelope detectors (for AM detection) arranged in such a manner that the output voltages across R_1 and R_2 are in opposition. At I.F. resonance frequency (10.7 MHz) the voltages are equal and the output of the discriminator is zero. At frequencies above and below 10.7 MHz, however, the voltage output of the discriminator varies at an audio rate controlled by the modulation frequency of the original FM signal. The final characteristic curve for this type of discriminator is similar to that shown in Figure 8.

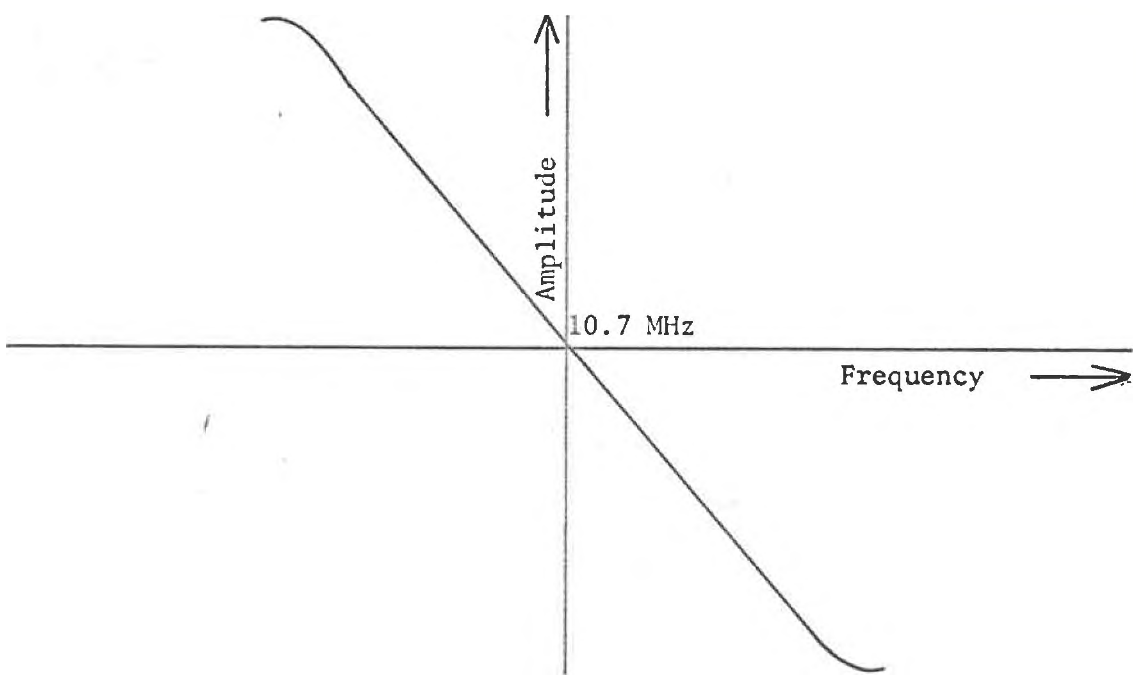


Figure 8 - Output Characteristic Curve

Phase Discriminator

Phase discriminators are probably the most widely-used type of FM detector in commercial radio. This type of circuit is also known as the Foster-Seeley Discriminator. A typical circuit is shown in Figure 9. The technique used for detection of an FM signal in this circuit is as follows:

a. Incoming FM signals at an I.F. frequency of 10.7 MHz are amplitude-limited through the limiter tube to eliminate any AM that may be "riding" on the FM signal.

b. Tank circuit "A" is tuned to 10.7 MHz with a wide enough bandwidth so as not to introduce amplitude variations of the FM signal at this point. The output of this tank circuit is symbolically shown in Figure 6.

c. Tank circuit "B" is also tuned to 10.7 MHz. Therefore, an FM to FM-AM conversion is not performed by this discriminator. Of importance to this circuit are: 1) the secondary coil is center-tapped,producing a voltage division (E_2 across L_2 and E_3 across L_3), 2) the voltage across L_1 (E_1) is almost the same across L (E_1), and 3) the phase relationship between E_2 and E_1, and E_3 and E_1 [3].

d. At resonance (10.7 MHz) tank circuit "B" appears resistive and the induced voltage and current are in phase as shown in Figure 10.

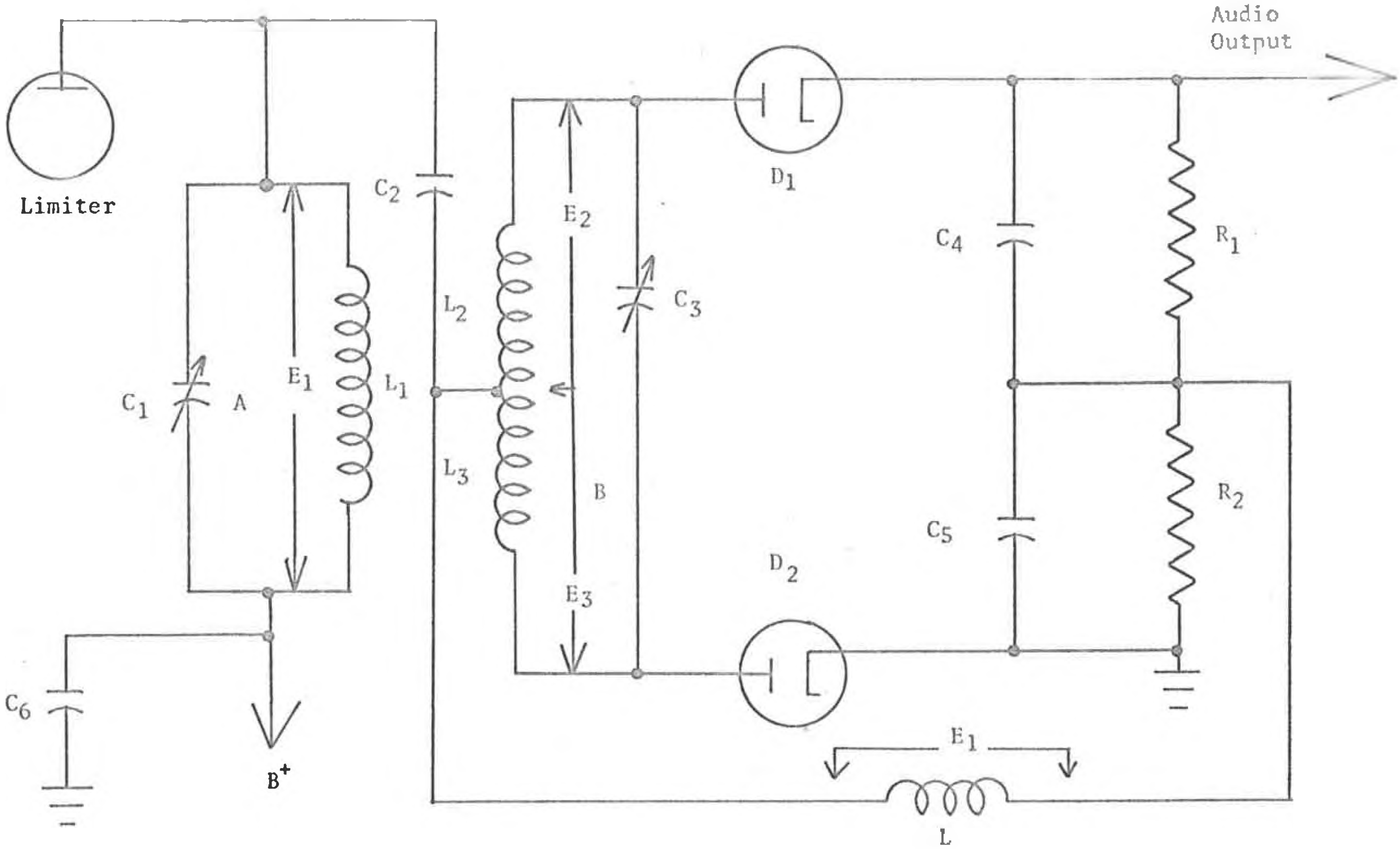


Figure 9 - Phase Discriminator

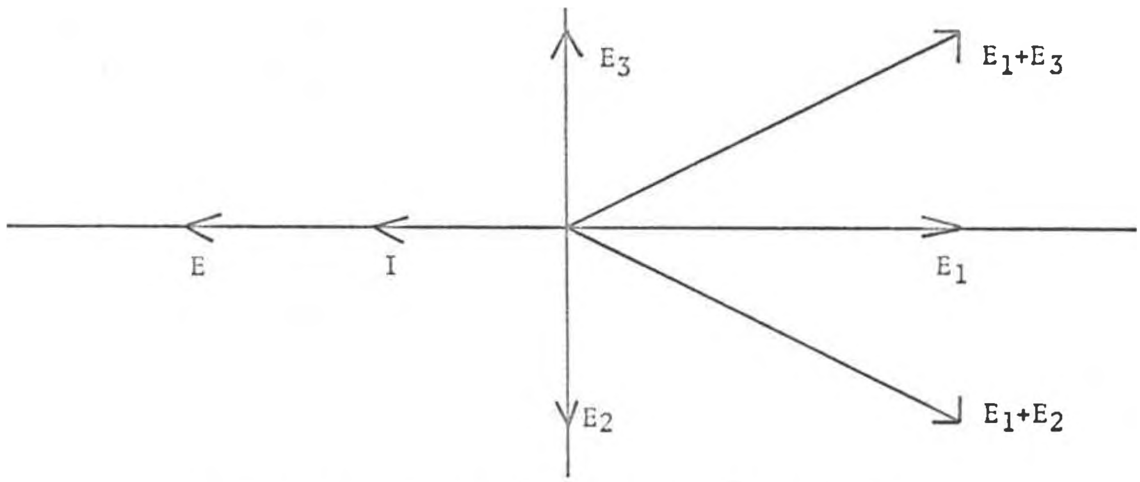


Figure 10 - Phase Relationships At Resonance

Note that E_1 in the primary coil and E, the induced voltage in the secondary coil, are 180° out of phase and also that E_2 and E_3 while out of phase by 180° effectively lead and lag the induced current I by 90°. Therefore, the voltage that appears across R_1 and R_2 (E_1+E_2 and E_1+E_3 respectively) cancel each other and there is no output from the discriminator.

e. At frequencies higher than resonance, tank circuit "B" appears inductive and the induced current I lags the voltage by an amount determined by the modulating frequency as shown in Figure 11. Therefore the voltage that appears across R_1 and R_2 will vary at an audio rate determined by the modulating frequency of the FM signal.

f. At frequencies below resonance, tank circuit "B" appears capacitive and the induced current I leads the voltage by an amount determined by the modulating frequency as shown in Figure 12.

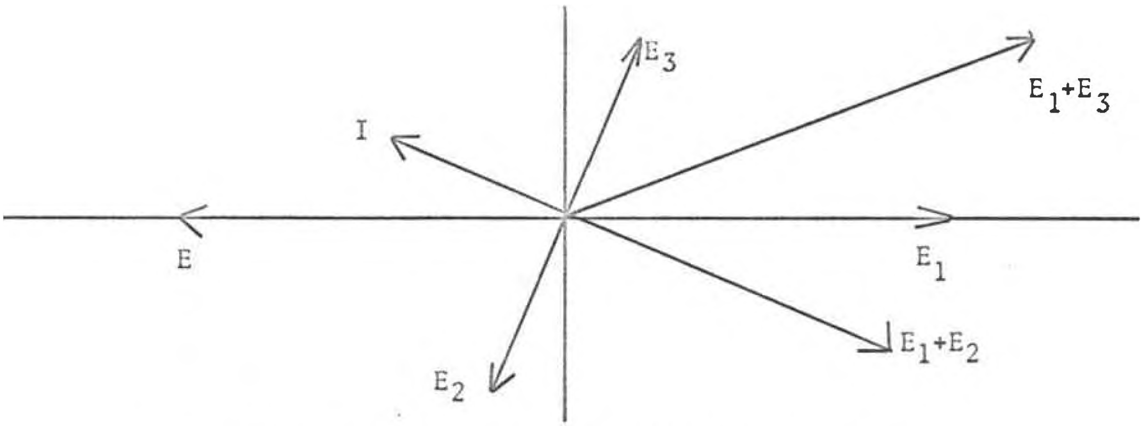


Figure 11 - Phase Relationships Above Resonance

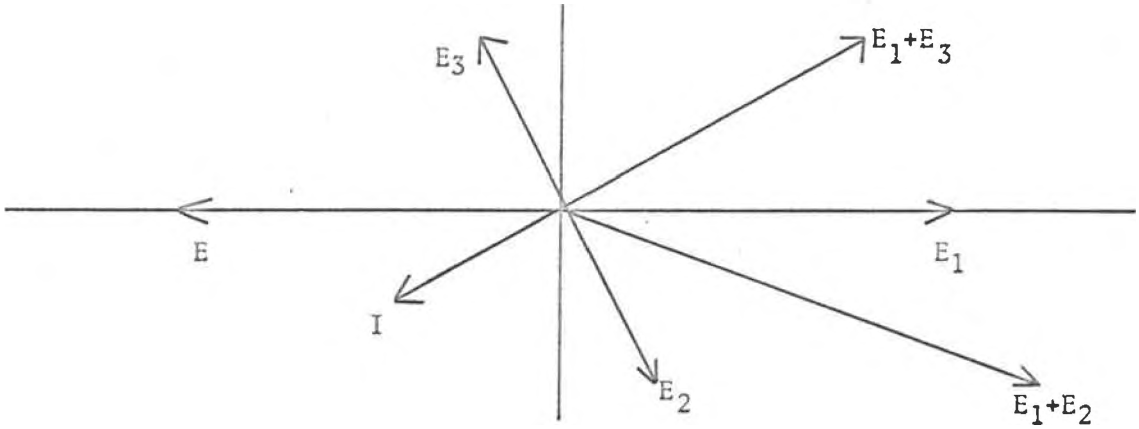


Figure 12 - Phase Relationships Below Resonance

The voltages that appear across R_1 and R_2 will still vary at an audio rate as in the case of frequencies above resonance. However, the sum of the voltages appearing across R_1 and R_2 below resonance will be opposite in polarity to the sum of voltages across R_1 and R_2 above resonance. The final characteristic curve for this type of discriminator will be similar to Figure 8.

Ratio Detector

Ratio detectors are popular in FM detection circuits that are not preceded by a limiter. The basic ratio detector is shown in Figure 13. The technique used for detection of an FM signal in this circuit is as follows:

a. Tank circuit "A" is tuned to 10.7 MHz with a wide enough bandwidth so as not to introduce amplitude variations of the FM signal at this point.

b. Tank circuit "B" is also tuned to 10.7 MHz. Therefore an FM to FM-AM conversion is not performed by this detector. As a matter of fact, this circuit has the same phase relationship as the phase discriminator. However, resistors R_1 and R_2 do not exist and therefore the voltage potentials E_1+E_3 and E_1+E_2 are across C_2 and C_3 respectively.

c. The diodes are in "series aiding" as opposed to the frequency and phase discriminators. Also, a form of biasing is produced by the RC circuit at such a long time constant that for all

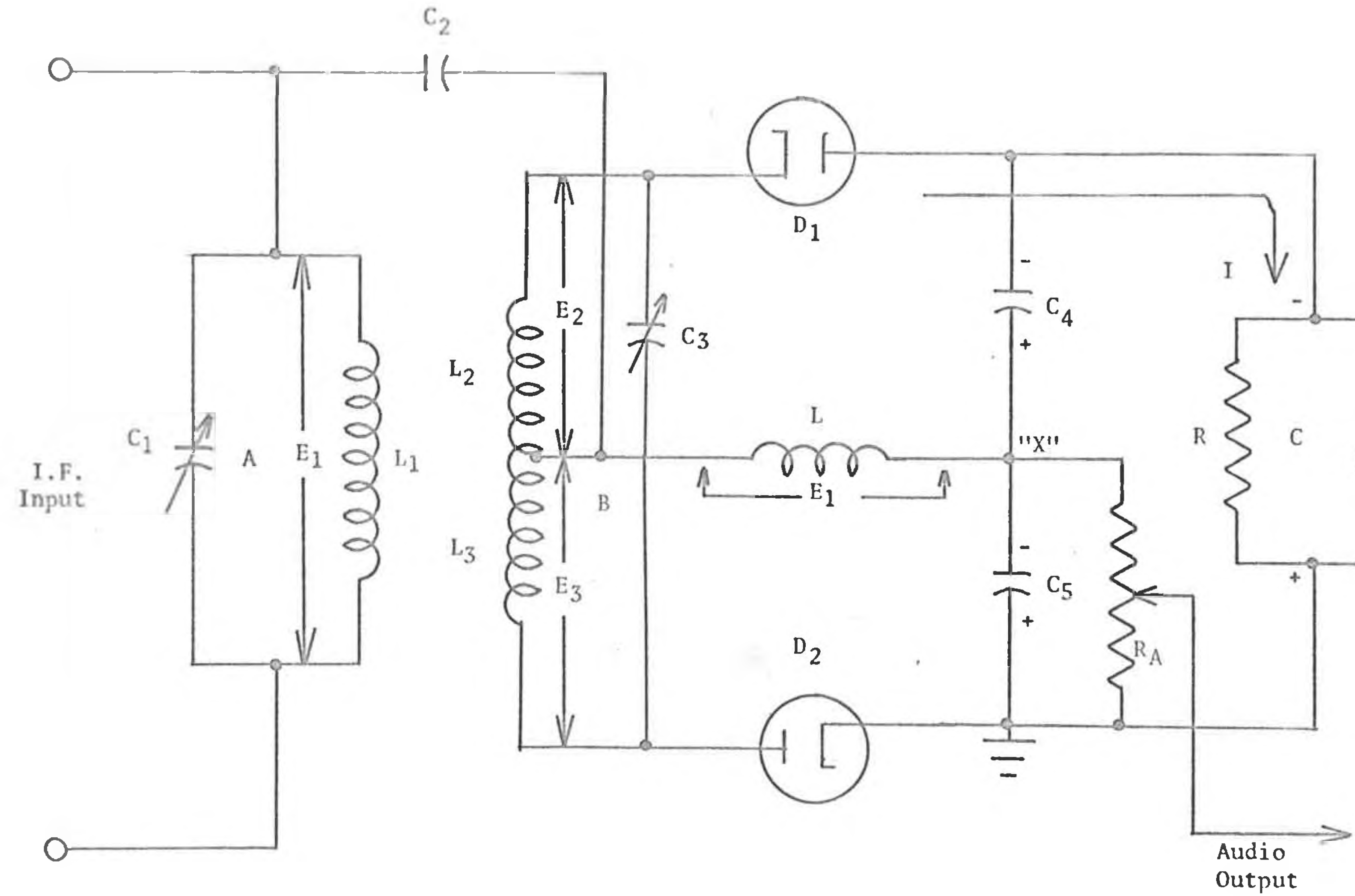


Figure 13 - Ratio Detector

intents and purposes it acts as a battery. The charges (positive or negative) shown in Figure 13 are constant. Therefore, the sum of the voltages is always constant and equal to the voltage across R. The voltages across C_4 and C_5 vary in proportion to the modulation of the FM signal.

d. At resonance the voltages across C_4 and C_5 are equal and the audio frequency voltage at point "X" is zero with respect to ground.

e. As the FM signal is modulated above and below center frequency, the audio frequency voltage between point "X" and ground varies in proportion to the modulating signal. The resultant output has a characteristic curve similar to Figure 8.

f. AM is prevented from affecting the circuit because of the RC circuit. The RC network maintains a biasing potential on capacitors C_4 and C_5 based on the strength of the incoming signal. If AM is present on the FM it will attempt to increase the voltages across C_4 and C_5. However, the biasing effect does not permit this unbalance (the sum of the voltages across capacitors C_4 and C_5 equals the bias voltage). This is due to the long time constant of the RC circuit which does not permit the voltage across R to change fast enough to accommodate the AM.

Slope Detector

Slope detection is basically conversion of the FM signal to FM-AM and detection of the AM by rectifier detection techniques (usually envelope detection). The slope detection circuit used for FM detection in this paper is shown in Figure 15. The technique used for detection of an FM signal in this circuit is as follows:

a. The incoming I.F. FM signal is centered at 530 KHz. The tank circuit is the I.F. tank circuit for an AM radio and is resonant at 455 KHz as shown in Figure 14.

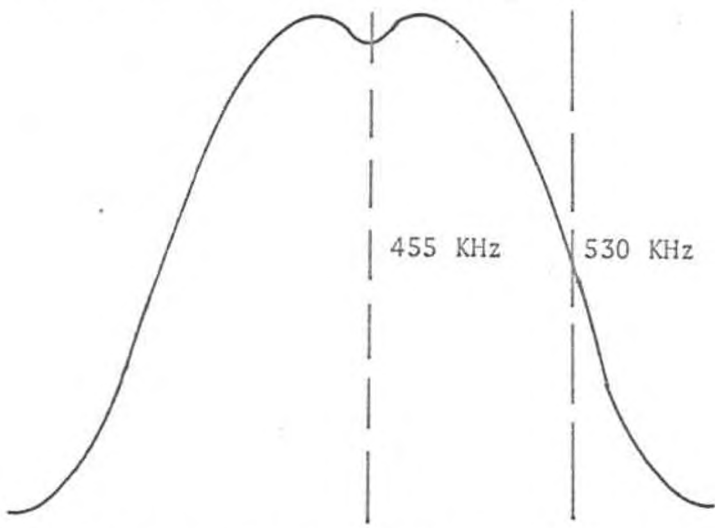


Figure 14 - AM Radio I.F. Response Curve

b. FM to FM-AM conversion takes place due to the centering of the FM signal on the linear portion of the response curve.

c. The FM-AM signal is now detected by the envelope detector of the AM radio and is then passed on for audio amplification.

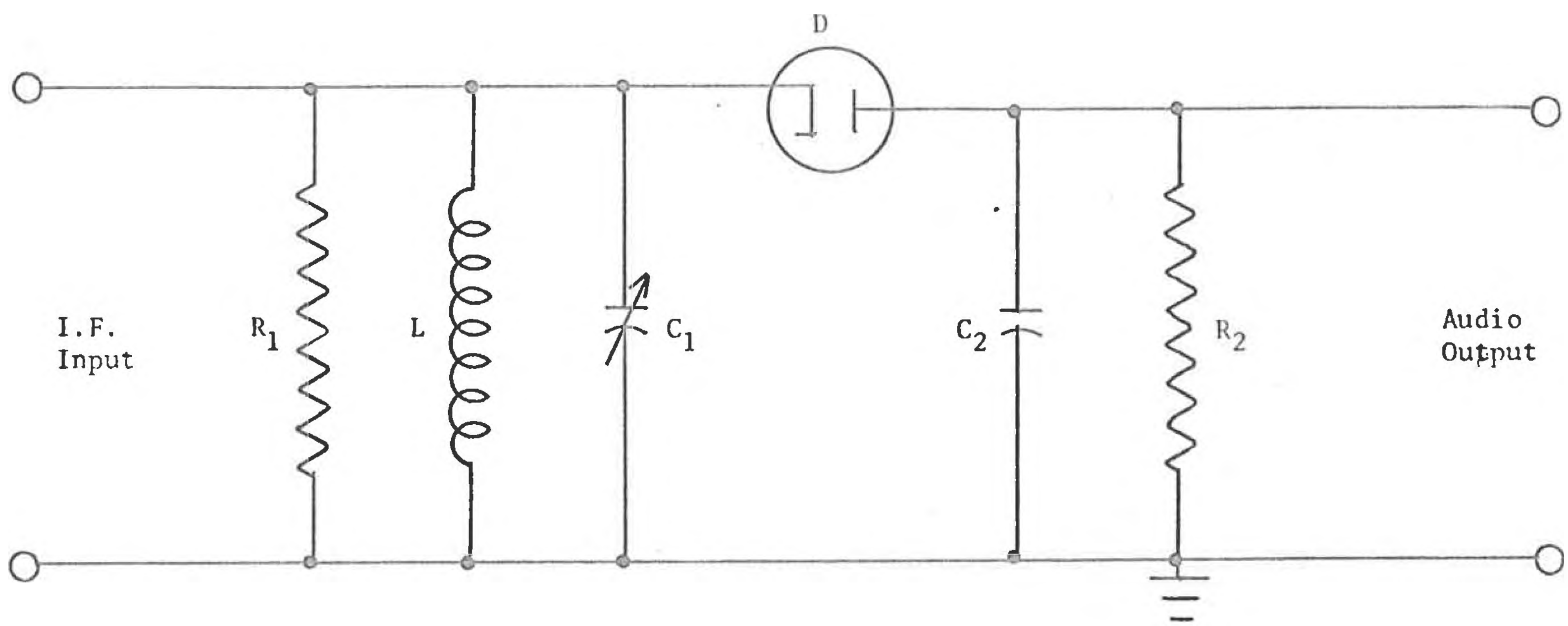


Figure 15 - Slope Detector

Comparison of the FM detectors described is made in Table 1. Reference will be made to this Table in arriving at conclusions to the applicability of slope detection in commercial FM/AM radios in Chapter VIII.

Table 1

Comparison of FM Detectors

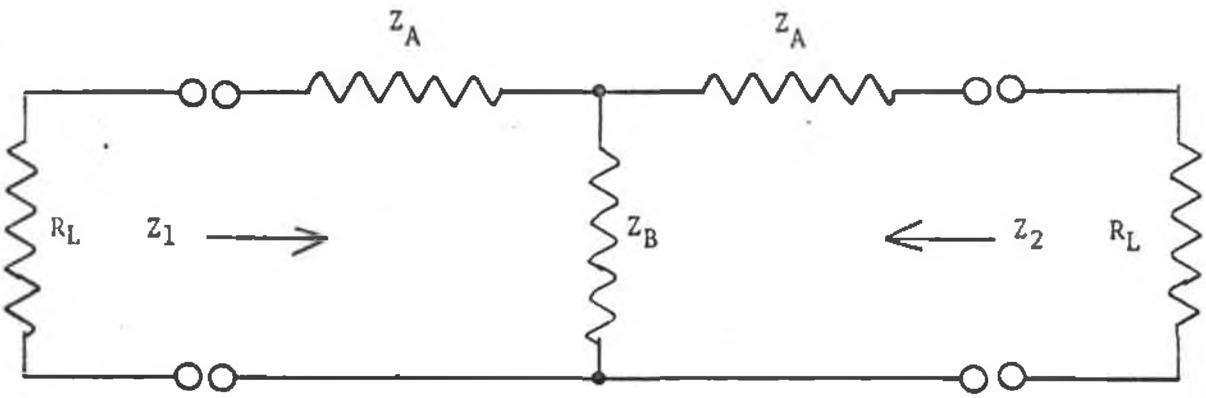
	Frequency Discriminator	Phase Discriminator	Ratio Detector	Slope Detector
Detection Technique	Slope	Phase	Phase-Ratio	Slope
AM Distortion Eliminator	Limiter	Limiter	RC Bias Circuit	Limiter
Number Of Tuned Circuits	3	2	2	1
Output Chacter-istic	Figure 8	Figure 8	Figure 8	Figure 14
Symmetry Balance Required	Crucial for output slope linearity	Crucial if proper phas-ing is to be achieved	Critical for eliminaton of distortion	N/A
Phasing Between Primary & Secondary	Not crucial for detection	Critical	Critical	N/A
Diode Arrangement	Series Opposing	Series Opposing	Series Aiding	N/A
Slope Linearity	Good	Good	Good	Poor

IV. MATCHING NETWORKS

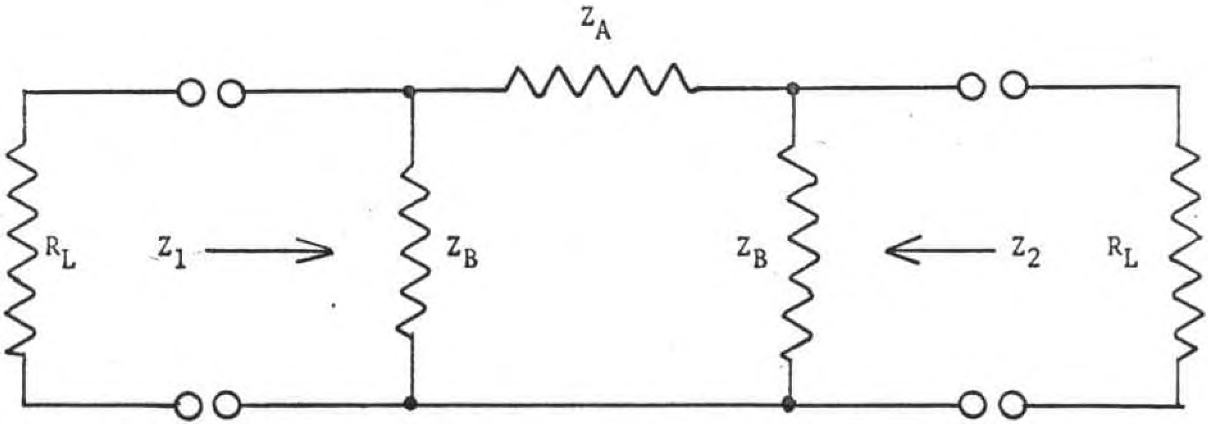
When two or more electrical networks are integrated to perform a function, it is ideal to have all network source impedances equal. This is required for maximum signal transfer with minimum VSWR. However, such an ideal situation is not always the case. Realistically, this condition can be realized by placing a matching network between sources.

It is desired that through a matching network, image impedances will be equal. To obtain this equality, passive symmetric networks of the "T", "Π" and "LATTICE" types were considered and are shown in Figure 16. Z_1 and Z_2 of Figure 16 are image impedances and are defined as the impedances looking into either terminals of the matching network. The matching network selected from the above mentioned three types of networks would be integrated between the FM radio - local oscillator - mixer combinations, mixer - bandpass filter combination, and bandpass filter - AM radio combination.

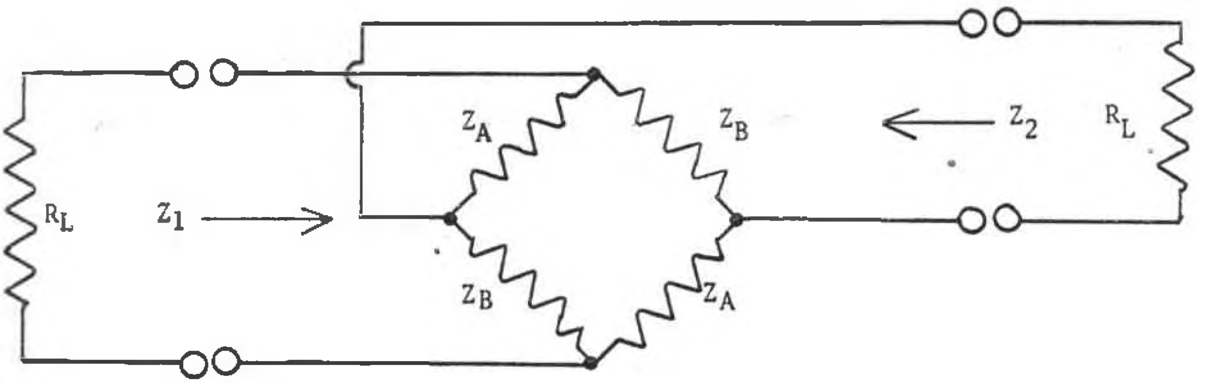
Since most of the transfer network between FM radio and AM radio is passive, it is desirable to have a matching network of little attenuation. This must be directly correlated with minimum VSWR. Such a correlation can be determined from the nomograph of Figure 17 [6]. Analysis of Figure 17 indicates that 10 db of attenuation would yield the best reduction in VSWR with a minimum value



a) "T" Matching Network



b) "Π" Matching Network



c) "LATTICE" Matching Network

Figure 16 - Symmetric Matching Networks

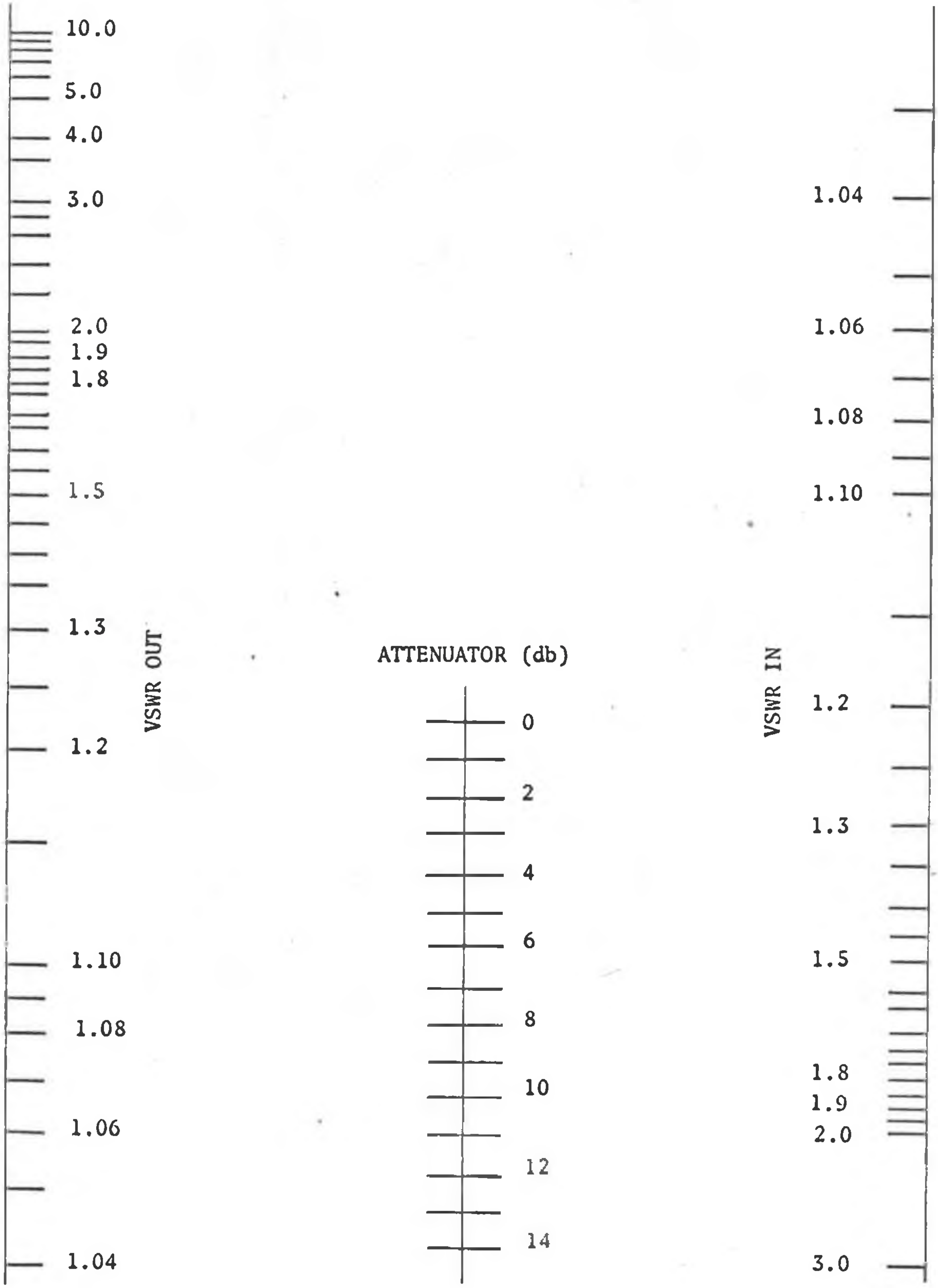


Figure 17 - Reduction Of VSWR As A Function Of Attenuation

of attenuation. On this basis, the three types of networks were evaluated.

Considering first the "T" network, a value was assigned resistance Z_A (=70Ω) and then evaluated for a transfer function furnishing 10 db of attenuation as shown in Figure 18.

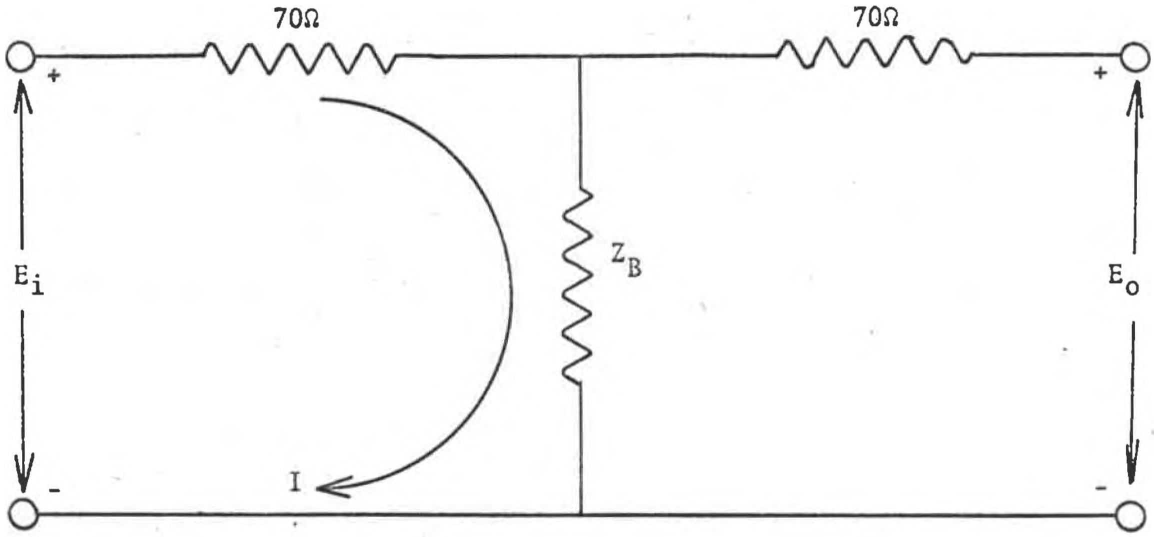


Figure 18 - "T" Network Analysis

Applying loop analysis one obtains

$$E_{in} = (70+Z_B)I \tag{1}$$

$$E_{out} = Z_B I \tag{2}$$

$$E_{out}/E_{in} = Z_B/70+Z_B \tag{3}$$

but

$$E_{out}/E_{in} = 0.316 \quad \text{(for 10 db attenuation)} \tag{4}$$

therefore

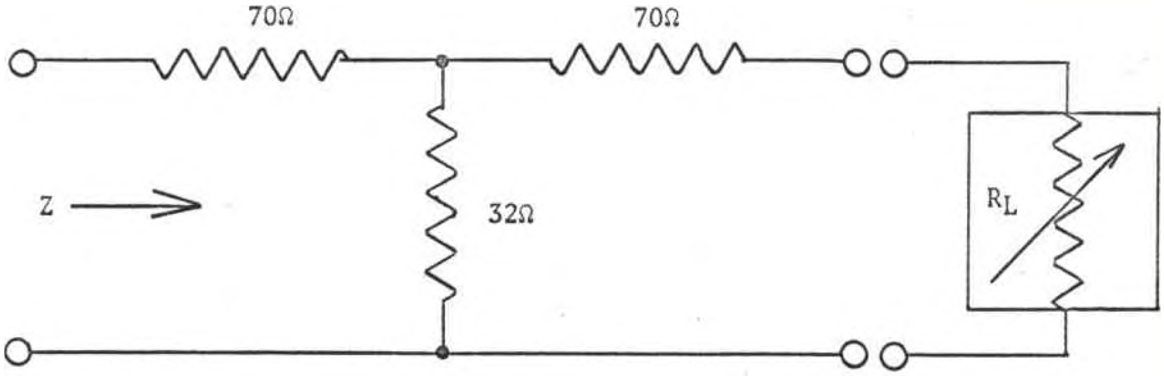
$$E_{out}/E_{in} = 0.316 = Z_B/70+Z_B \tag{5}$$

$$Z_B = 31.9\Omega \tag{6}$$

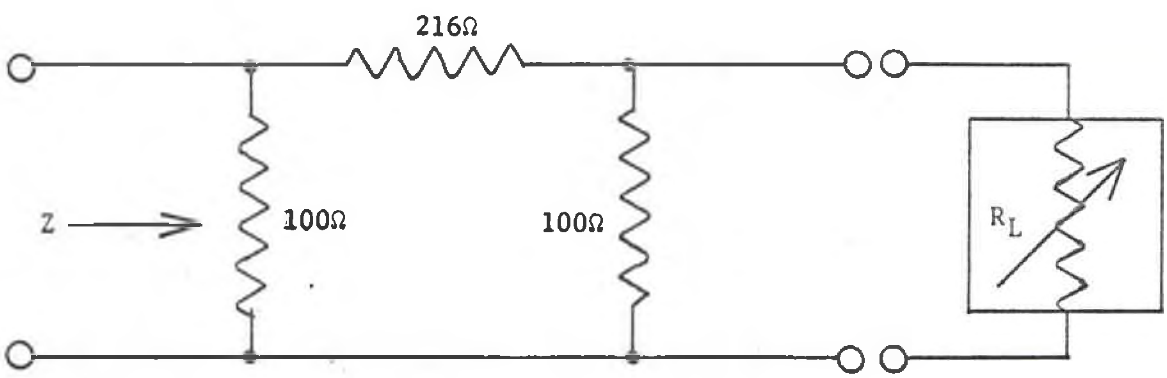
Similar analysis was performed on "Π" and "LATTICE" type networks with the following results:

"Π" network:	$Z_A = 216\Omega$	(evaluated)
	$Z_B = 100\Omega$	(assumed)
"LATTICE" network:	$Z_A = 100\Omega$	(assumed)
	$Z_B = 192.5\Omega$	(evaluated)

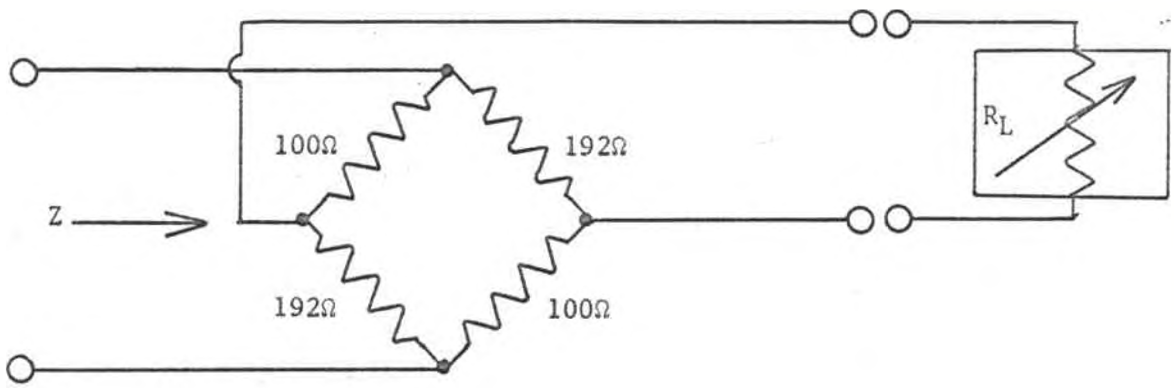
To determine the consistancy of image impedance values under varying loads, Figure 19 was used in evaluating the parameters of Table 2. The values obtained in Table 2 are plotted in Figure 20. As can be seen from Figure 20, none of the image impedances for the various types of networks vary to any great extent. It can then be concluded that any one of the three type networks could be utilized. The choice of utilizing the "T" type network was made because 1) consistency of design with the passive "T" type mixer network as described in Chapter V and 2) resistors with proper resistance values (commercially available) were satisfactory for this network.



a) "T" Matching Network



b) "Π" Matching Network



c) "LATTICE" Matching Network

Figure 19 - Symmetric Matching Networks

Table 2

Varying Load Measurements

NETWORK	LOAD - $R_L(\Omega)$	IMAGE IMPEDANCE $Z(\Omega)$
"T"	0	91.95
	100	96.00
	300	99.50
	500	100.40
	1000	101.00
"Π"	0	68.40
	100	72.70
	300	74.40
	500	75.00
	1000	75.60
"LATTICE"	0	131.40
	100	137.00
	300	141.40
	500	142.50
	1000	144.35

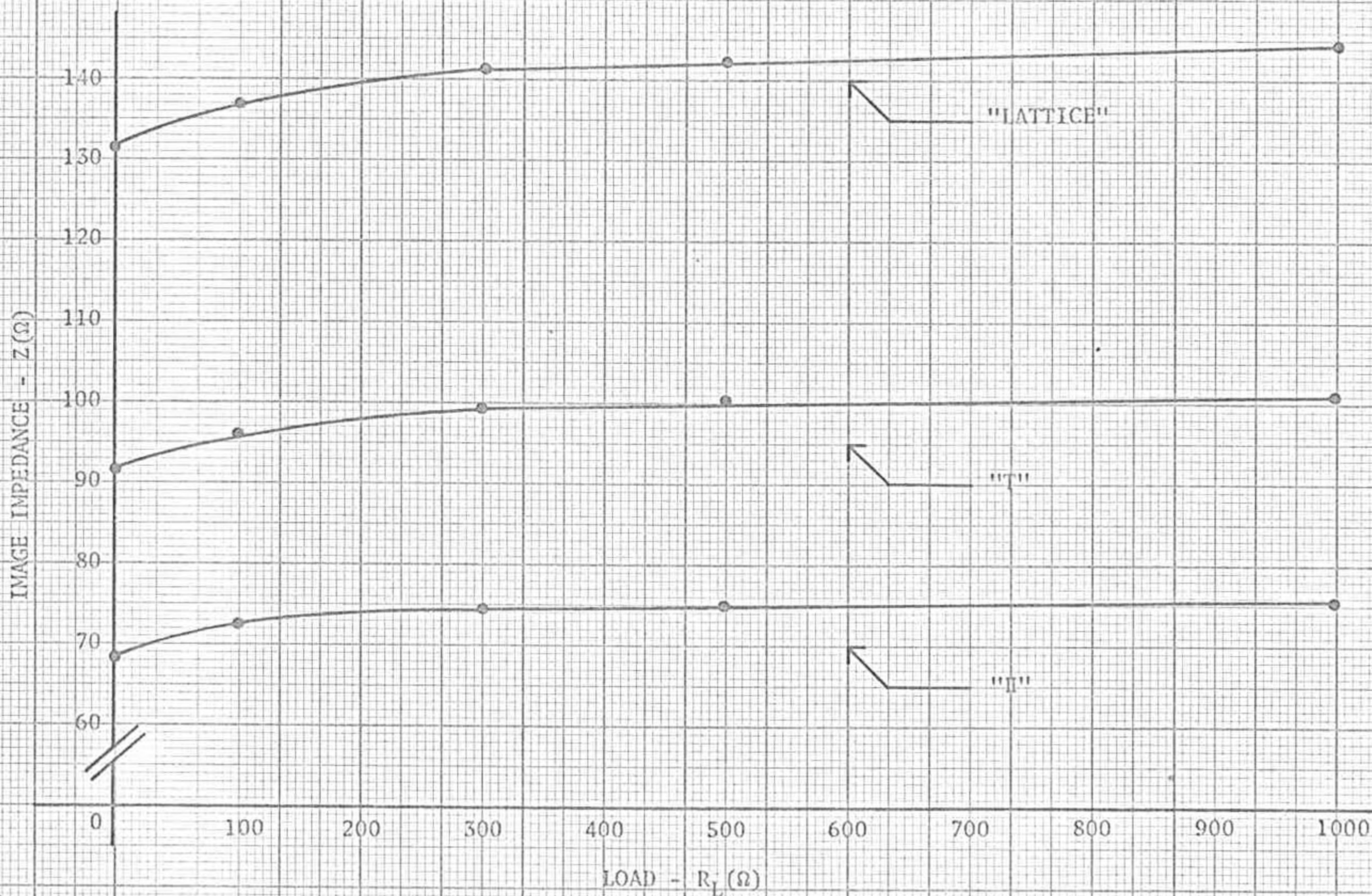


Figure 20 - Image Impedance vs Load Impedance

V. MIXER DESIGN

The choice of an appropriate mixer in a heterodyne type system is essentially critical. Due to the mixer in such a system, undesired signals may be formed if care is not taken initially in design.

For the system (integration circuitry between FM and AM radios) demonstrated in this paper, a double conversion is actually taking place. The first conversion is made by the FM radio itself from an rf input signal to a 10.7 MHz ±75 KHz I.F. signal. At this point the signal is down converted again by the circuitry of section (c) of Figure 3.

In heterodyne type systems, it is standard for the local oscillator to be higher in frequency than that of the incoming rf signal. When mixed, their beat frequency becomes the I.F. signal. However, it is possible for an incoming signal to be higher in frequency than that of the local oscillator. In this case the beat frequency may be accepted as a legitimate I.F. signal. This is known as an image frequency. Also of detriment to a heterodyne type system are spurious responses due to harmonics of the local oscillator mixing with rf signals outside the desired input signal. Because of the double conversion performed by the integration circuitry between FM and AM radios, characteristics of heterodyning such as these described, are virtually eliminated. This is partially due to the circuitry of the FM radio ahead of the I.F. tap but mainly due to the constant frequency input to the mixer of 10.7 MHz ±75 KHz.

It is due primarily to the double conversion of the FM signal, then, that the design of the mixer in this paper is limited basically to attenuation and matching with input and output circuitry only.

Constant-impedance mixers were chosen for this paper due to the constant impedances into the mixer from the FM signal amplifier and the local oscillator. Of the constant impedance mixers there can be found a variety of configurations such as "T", "Π", bridge, coil, etc. The "T" configuration was chosen for its basic simplicity and availability of resistors. In choosing an arrangement of "T" networks (i.e. parallel, series, etc) consideration must be given to both "grounding" problems as well as mixing loss. Two such networks are shown in Figure 21. In computing mixing loss of the networks shown in Figure 21, we must consider the following [4]:

Parallel:

$$\text{Mixing Loss} = 20 \log_{10} n \tag{7}$$

where n = number of inputs (=2)

substituting:

$$\text{Mixing Loss} = 20 \log_{10} 2 = \underline{6.02 \text{ db}} \tag{8}$$

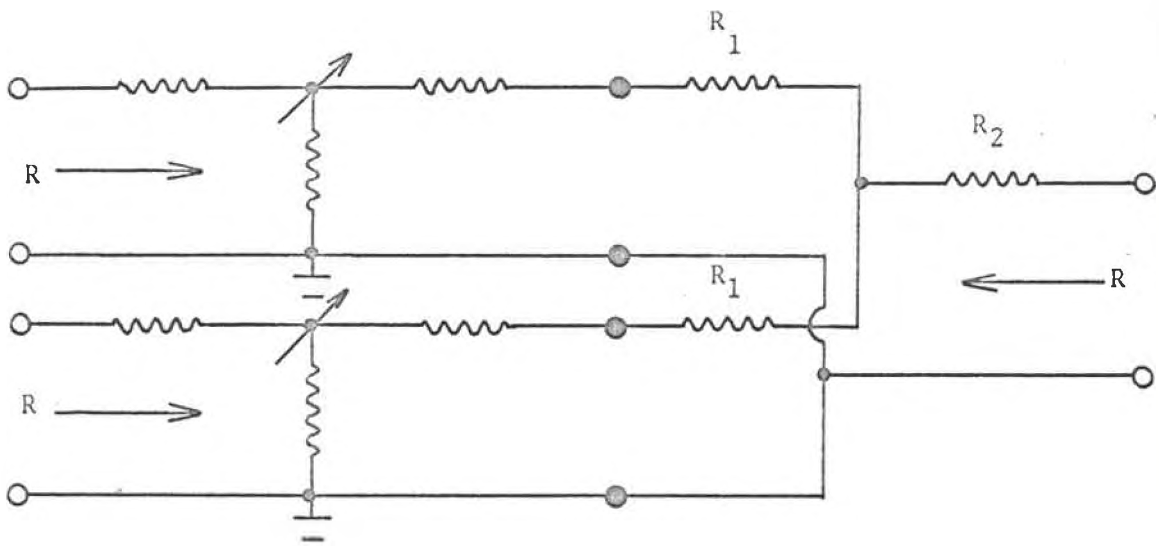
Series:

$$\text{Mixing Loss} = 10 \log_{10} (2n-1) \tag{9}$$

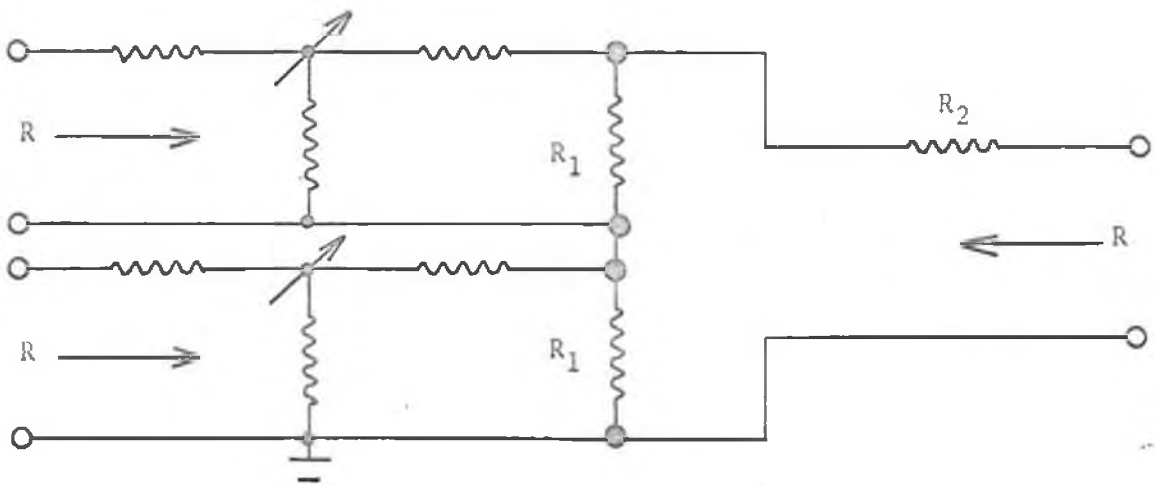
where n = number of inputs (=2)

substituting:

$$\text{Mixing Loss} = 10 \log_{10} 3 = \underline{4.77 \text{ db}} \tag{10}$$



a) "T" Network In Parallel



b) "T" Network In Series

Figure 21 - Mixer Networks

From the above calculations, it is readily seen that for minimum mixing loss the best approach is to use the "series T" network. However, when considering "grounding" of the mixer, the "parallel T" network is more desirable. This is due primarily to the grounding problems associated with the integration circuitry between (and including) the FM and AM radios. A common ground is necessary for compatibility and is provided by the "parallel T" network. The "series T" network, on the other hand necessitates having one of the "T" pads above ground. Therefore, accepting a higher mixing loss for a more preferred grounding system, the "parallel T" network was chosen for the mixer circuit.

Since the front end of the mixer chosen is a "T" pad, the value of "R" in Figure 21a is 100Ω. This value was chosen in order to be consistent with all matching networks (see Chapter IV) of the system. Therefore all input and output impedances appeared as 100Ω to the mixer and the values of the resistors of the "T" pad were the same as the resistors of the "T"'s of the system matching networks. In general, the design equation for the desired mixer network is given as [4]:

$$R_1 = R_2 = R(n-1)/_{(n+1)} \tag{11}$$

where n = number of channels to be mixed

substituting n = 2; R = 100Ω:

$$R_1 = R_2 = 100(2-1)/_{(2+1)} = \underline{33.3\Omega} \tag{12}$$

This network output now supplies mixing of the FM signal and local oscillator signal. To achieve the desired signal (difference frequency = 530 KHz), the two signals must be passed through a nonlinear device to obtain sum and difference frequencies. A diode of low forward impedance was chosen for the nonlinear device.

The entire mixer network to perform the desired output signal is shown in Figure 22.

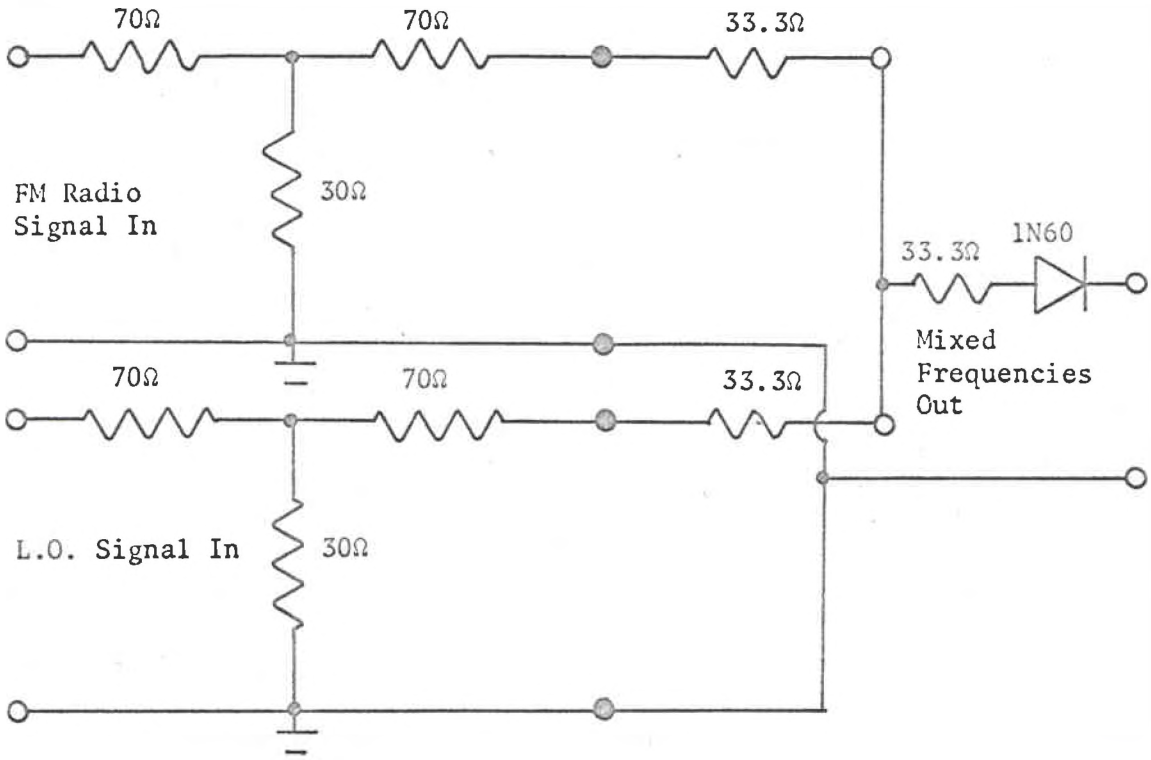


Figure 22 - Total Mixer Network

The diode of the mixer network essentially performs the function of modulating the FM signal with the local oscillator signal. Choosing the FM signal and local oscillator signal as functions of voltage, we assume the following equations:

$$e_c = \sqrt{2}\, E_c \cos(\omega_{c_{FM}} + M_f \sin \omega_{m_{FM}})t \qquad (13)$$

$$e_m = \sqrt{2}\, E_m \cos(\omega_c)t \qquad (14)$$

where e_c = FM signal

e_m = local oscillator signal

The voltage function for a nonlinear device is given as:

$$e_o = a_o + a_1 e_i + a_2 e_i^{\,2} \tag{15}$$

where

$$e_i = e_c + e_m \tag{16}$$

substituting:

$$\begin{aligned} e_o = a_o &+ a_1[\sqrt{2}E_c \cos(\omega_{c_{FM}} + M_f \sin \omega_{m_{FM}})t + \sqrt{2}E_m \cos(\omega_c)t] \\ &+ a_2[\sqrt{2}E_c \cos(\omega_{c_{FM}} + M_f \sin \omega_{m_{FM}})t + \sqrt{2}E_m \cos(\omega_c)t]^2 \end{aligned} \tag{17}$$

evaluating:

$$\begin{aligned} e_o = a_o &+ \underbrace{a_1[\sqrt{2}E_c \cos(\omega_{c_{FM}} + M_f \sin (\omega_{c_{FM}})t]}_{e_c} \\ &+ \underbrace{a_1[\sqrt{2}E_m \cos(\omega_c)t]}_{e_m} \quad \underbrace{+a_2[E_c^{\,2}] + a_2[E_m^{\,2}]}_{D.C.} \\ &\underbrace{+a_2[E_c^{\,2}\cos(2\omega_c)t] + a_2[E_m^{\,2}\cos 2(\omega_{c_{FM}} + M_f \sin \omega_{m_{FM}})t]}_{\text{Second Harmonics}} \\ &\underbrace{+a_2[2E_cE_m \cos(\omega_c t - [\omega_{c_{FM}}t + M_f \sin \omega_{m_{FM}}t])]}_{\text{Difference}} \\ &\overbrace{+a_2[2E_cE_m \cos(\omega_c t + [\omega_{c_{FM}}t + M_f \sin \omega_{m_{FM}}t])]}^{\text{Sum}} \end{aligned} \tag{18}$$

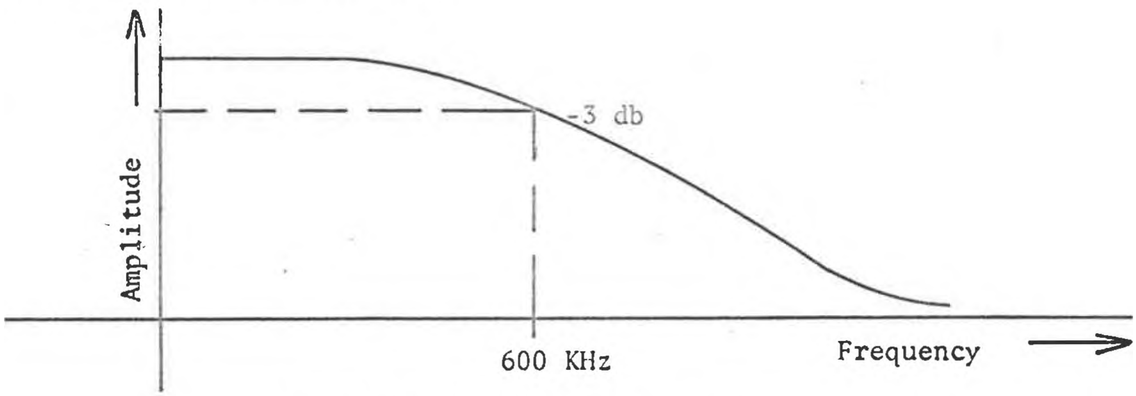
The above output of the mixer (e_o) is now passed through a bandpass filter which attenuates all of the above signals except the difference frequency. This signal is favored by the filter and is passed on for detection in the AM radio.

VI. DIFFERENCE FILTER

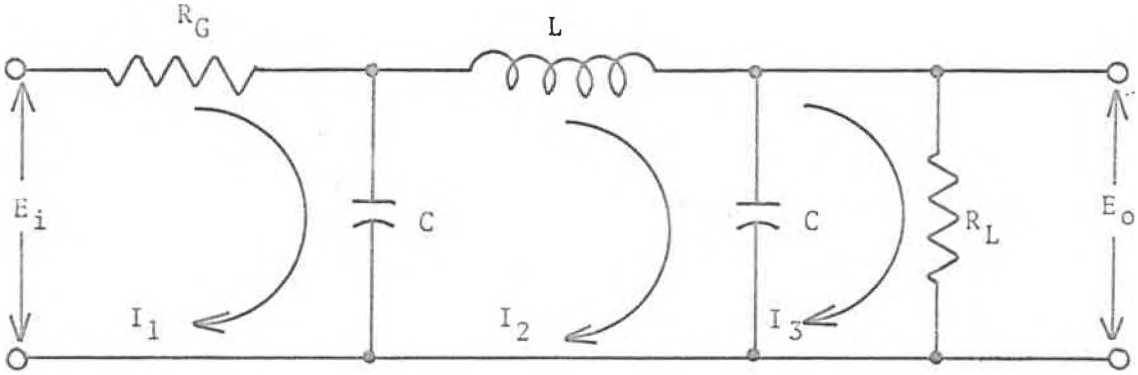
At the output of the mixer, filtering is required in order to select the desired signal (difference frequency) and attenuate the other signals present. Since the I.F. transformer of the AM radio performs a filtering function, the difference filter at the output of the mixer performs additional filtering not necessarily required but of some benefit in controlling Radio Frequency Interference (RFI). This filter is, therefore, not primarily concerned with the absolute filtering of the 530 KHz ±75 KHz signal, but rather an attenuation of other frequencies outside of this range. Therefore, a general filter design approach was taken in obtaining a filter to perform the above described function.

To provide filtering for detection of difference frequencies on either the positive or negative portion of the I.F. response curve and also allowing FM signal deviations of ±100 KHz (this includes a ±25 KHz guard band), a filter bandwidth of 600 KHz (measured at the 3 db points) had to be realized. This bandwidth also includes ±50 KHz guard band around the curved portion of the I.F. response curve (455 KHz ±50 KHz). To reduce harmonics as well as other undesirable signals above and below 455 KHz, a bandpass filter with center frequency of 455 KHz and 3 db bandwidth of 600 KHz was considered to be best suited in meeting all the requirements of the difference filter.

A bandpass filter is readily designed through first designing a low pass filter with a 3 db down point at a frequency which is the difference between the desired bandwidth of the bandpass filter and zero [5]. For consideration in this paper, the 3 db down point is at 600 KHz as shown in Figure 23a. After the circuit parameters are determined from the transfer function of the low pass filter, it is a simple matter of adding a capacitor or inductor in series or parallel (respectively) that are resonant at the center frequency of the desired bandpass filter.



a) Low Pass Filter Response



b) Low Pass Filter Circuit

Figure 23 - Low Pass Filter

From the circuit of Figure 23b, the following calculations were made to determine the parameters of the low pass filter:

assume: R_G = resistance of generator = 100Ω

R_L = resistance of load = 100Ω

performing loop analysis we obtain:

$$E_{in}(S) = (100+\frac{1}{CS})I_1 - \frac{1}{CS}I_2 \tag{19}$$

$$E_{out}(S) = 100\ I_3 \tag{20}$$

$$0 = -\frac{1}{CS}I_1 + (\frac{2}{CS}+LS)I_2 - \frac{1}{CS}I_3 \tag{21}$$

$$0 = -\frac{1}{CS}I_2 + (100+\frac{1}{CS})I_3 \tag{22}$$

and

$$E_{out}(S)/E_{in}(S) = 100I_3 / (100+\frac{1}{CS})I_1 - \frac{1}{CS}I_2 \tag{23}$$

solving for I_2 in Equation (22)

$$I_2 = (100CS+1)I_3 \tag{24}$$

solving for I_1 in Equation (21)

$$\frac{1}{CS}I_1 = (\frac{2}{CS}+LS)(100CS+1)I_3 - \frac{1}{CS}I_3 \tag{25}$$

$$I_1 = (200CS+100LC^2S^3+LCS^2+1)I_3 \tag{26}$$

evaluating Equation (23) from (24) and (26)

$$E_{out}(S)/E_{in}(S) = 100I_3 / (100+\frac{1}{CS})(200CS+100LC^2S^3+LCS^2+1)I_3 - \frac{1}{CS}(100CS+1)I_3 \tag{27}$$

$$E_{out}(S)/E_{in}(S) = 100/S^3(LC^2x10^4)+S^2(200LC)+S(2x10^4C+L)+200 \quad (28)$$

substituting $S = j\omega$

$$E_{out}(j\omega)/E_{in}(j\omega) = 100/(j\omega)^3(LC^2x10^4)+(j\omega)^2(200LC)+j\omega(2x10^4C+L)+200 \quad (29)$$

dividing numerator and denominator by 100 and separating reals from imaginaries

$$E_{out}(j\omega)/E_{in}(j\omega) = 1/[2-2LC\omega^2]+j[-100LC^2\omega^3+200C\omega+\frac{\omega L}{100}] \quad (30)$$

rationalize Equation (30) by complex conjugate multiplication

$$\left|E_{out}(j\omega)/E_{in}(j\omega)\right|^2 = 1/[2-2LC\omega^2]^2+[-100LC^2\omega^3+200C\omega+\frac{\omega L}{100}]^2 \quad (31)$$

$$\left|E_{out}(j\omega)/E_{in}(j\omega)\right| = \left[1/[2-2LC\omega^2]^2+[-100LC^2\omega^3+200C\omega+\frac{\omega L}{100}]^2\right]^{1/2} \quad (32)$$

Equation (32) is the transfer function of the low pass filter of the circuit in Figure 23b. Circuit parameters can now be evaluated using this equation as follows:

assume: $C = 0.01\mu f = 10^{-8}f$

$\omega = 2\pi(600x10^3) = 37.68x10^5$

where R_G and R_L are image impedances of the networks into and out of the filter (see Chapter IV)

and

$$E_{out}/E_{in} = 0.707(0.5) = 0.3535 \quad (33)$$

where: 0.707 = half voltage point

0.5 = maximum output of filter for D.C. input

substituting Equation (33) and above assumption into Equation (32)

$$0.3535 = \left[{}^{1}/ [2-2L(10^{-8})(37.68x10^{5})^{2}]^{2}+[-100L(10^{-8})(37.68x10^{5})^{3} +200(10^{-8})(37.68x10^{5})+\frac{(37.68x10^{5})L}{100}]^{2} \right]^{1/2} \quad (34)$$

evaluating Equation (34) we obtain

$$L^{2} - 2.63x10^{-5}L + 1.61x10^{-10} = 0 \quad (35)$$

substituting in the quadratic equation

$$L = \frac{2.63x10^{-5} \pm \sqrt{6.92x10^{-10}-6.44x10^{-10}}}{2} \quad (36)$$

$$L = \frac{2.63x10^{-5}}{2} \quad (37)$$

$$L \simeq 1.315x10^{-5} \simeq \underline{13.15\mu h} \quad (38)$$

The parameters of the desired bandpass filter of Figure 24 can now be determined.

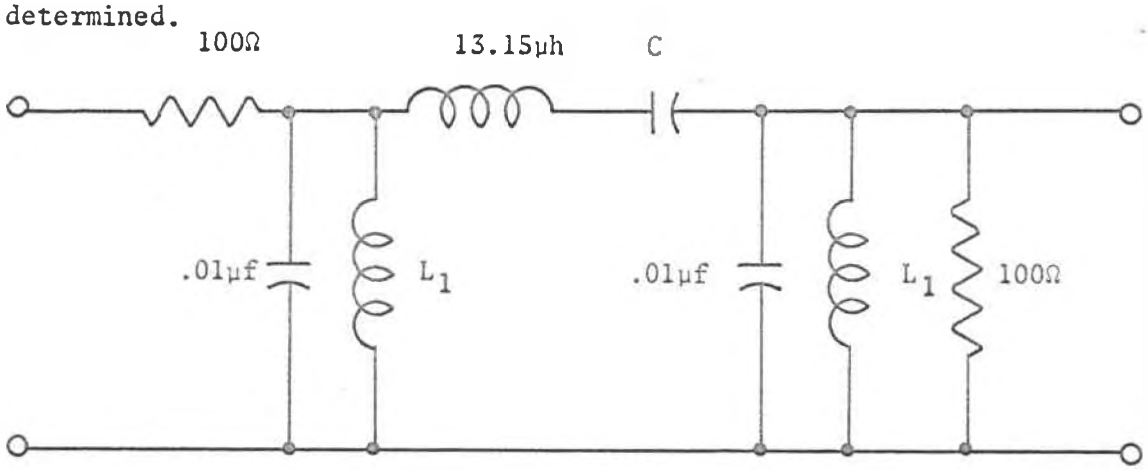


Figure 24 - Bandpass Filter Circuit

The following formula and assumption are made for resonance

$$\omega = {}^{1}/\sqrt{L_1 C} \tag{39}$$

assume: $\omega = 2\pi(455\text{x}10^3) \approx 2.86\text{x}10^6$

solving for L

$$2.86\text{x}10^6 = {}^{1}/\sqrt{L_1(10^{-8})} \tag{40}$$

$$L_1 = 0.0122\mu h \tag{41}$$

solving for C

$$2.86\text{x}10^6 = {}^{1}/\sqrt{(0.013\text{x}10^{-3})C} \tag{42}$$

$$C = 0.009\text{x}10^{-6} = \underline{0.009\mu f} \tag{43}$$

The solution to the transfer function for the bandpass filter is tedious and is susceptable to many mathematical errors. Therefore, in order to determine the response curve of the filter, empirical data was used and is shown in Table 3 and Figure 25. This Table and Figure were determined by a BPF circuit similar to that of Figure 24 but whose values were as follows:

all capacitors = $0.01\mu f$

all inductors = $11\mu h$

These values are a result of commercially-available components.

As can be seen by the filter response curve of Figure 25, the filter does not meet the desired requirements imposed on it initially due possibly to changes in parameter values because of commercial availability. The filter does have some acceptable features, however. The filter will attenuate those undesirable signals expected from the

Table 3

Bandpass Filter Response Values

Frequency (MHz)	E_i (volts)	E_o (volts)	E_o/E_i	Normalized E_o/E_i = X	20logX (-db)
00.050	8.0	0.000	0.00000	0.0000	----
00.100	8.0	0.000	0.00000	0.0000	----
00.200	8.0	0.006	0.00075	0.0176	35.10
00.350	8.0	0.210	0.02630	0.6000	4.44
00.400	8.0	0.240	0.03000	0.7050	3.04
00.450	8.0	0.290	0.03630	0.8300	1.62
00.475	8.0	0.320	0.04000	0.9420	0.52
00.500	8.0	0.340	0.04250	1.0000	0.00
00.530	8.0	0.340	0.04250	1.0000	0.00
00.550	8.0	0.340	0.04250	1.0000	0.00
00.575	8.0	0.320	0.04000	0.9420	0.52
00.600	8.0	0.300	0.03750	0.8820	1.10
00.650	8.0	0.260	0.03250	0.7650	2.32
00.700	8.0	0.240	0.03000	0.7050	3.04
00.750	8.0	0.230	0.02870	0.6750	3.40
00.800	8.0	0.235	0.02940	0.6910	3.20
00.850	8.0	0.250	0.03130	0.7360	2.66
00.900	8.0	0.280	0.03500	0.8240	1.68
00.950	8.0	0.310	0.03870	0.9100	0.82
01.000	8.0	0.270	0.03380	0.7950	2.00

Table 3 (continued)

Frequency (MHz)	E_i (volts)	E_o (volts)	E_o/E_i	Normalized $E_o/E_i = X$	20logX (-db)
01.100	8.0	0.140	0.01750	0.4120	7.50
01.200	8.0	0.080	0.01000	0.2350	12.58
01.250	8.0	0.060	0.00750	0.1760	15.10
01.300	8.0	0.050	0.00625	0.1470	16.66
01.400	8.0	0.030	0.00375	0.0882	21.08
01.500	8.0	0.010	0.00125	0.0294	30.64
01.800	8.0	0.008	0.00100	0.0235	32.58
20.000	8.0	0.020	0.00200	0.0470	26.56
23.500	7.2	0.040	0.00556	0.1310	17.66
24.000	7.2	0.050	0.00695	0.1635	15.74
25.000	7.2	0.080	0.01110	0.2620	11.64
26.000	7.2	0.070	0.00972	0.2280	12.84
27.000	7.2	0.050	0.00695	0.1630	15.76
28.000	7.2	0.050	0.00695	0.1630	15.76
29.000	8.0	0.060	0.00750	0.1760	15.10
30.000	8.8	0.040	0.00455	0.1070	19.40
40.000	11.0	0.110	0.01000	0.2350	12.58
43.000	5.2	0.030	0.00578	0.1360	17.32
45.000	4.4	0.020	0.00455	0.1070	19.40
47.000	4.4	0.030	0.00682	0.1600	15.92
50.000	4.4	0.040	0.00910	0.2140	13.40

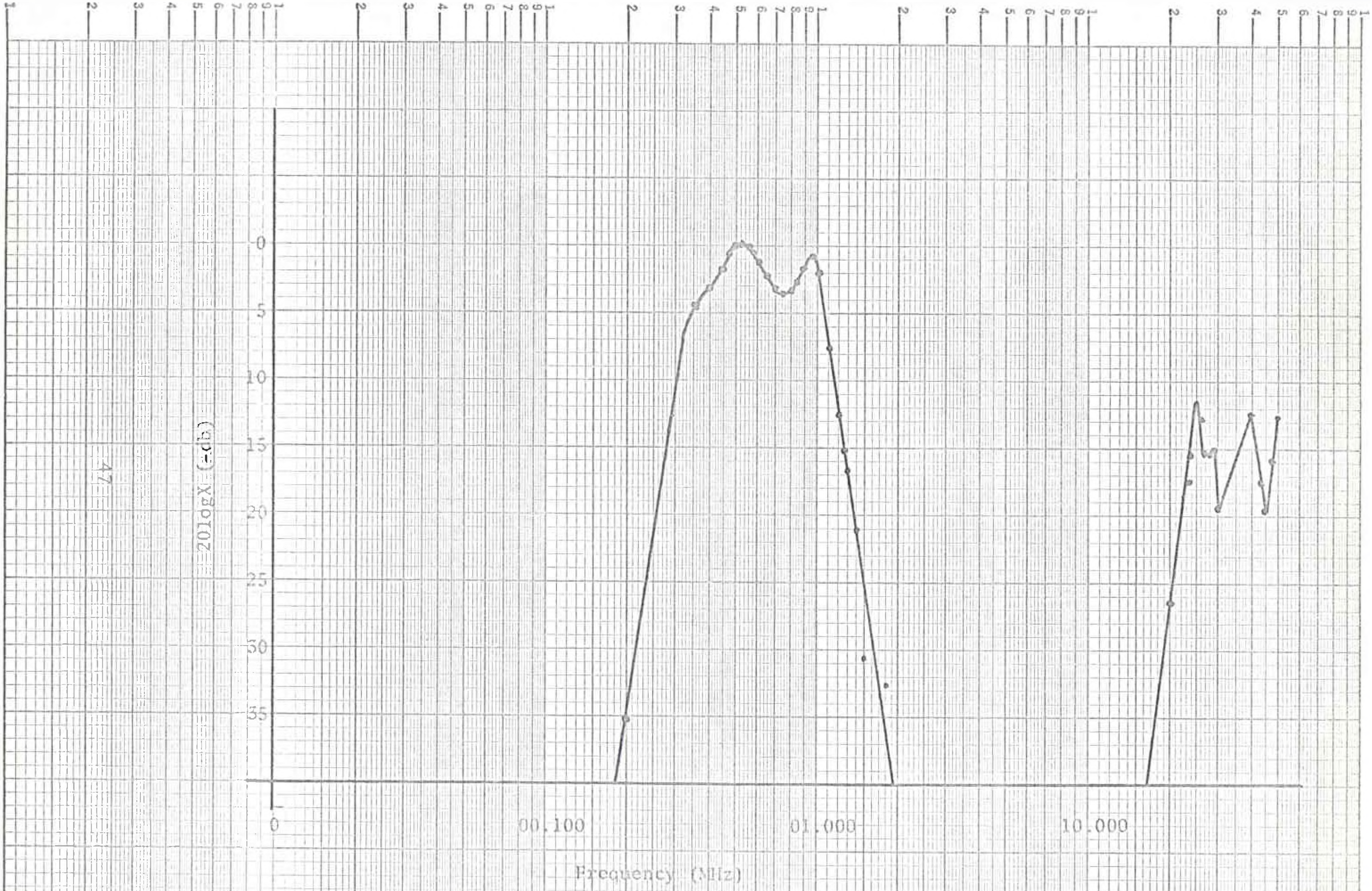


Figure 25 - Bandpass Filter Response

mixer. If the negative slope of the I.F. response curve is chosen for detection of the FM signal, the filter is sufficient. The filter peaks at 530 KHz and is a desirable center frequency point on the negative I.F. slope. The filter will not greatly attenuate the FM deviation of 530 KHz ±75 KHz. On the basis of the results shown here, the filter was determined to be acceptable and detection will be performed on the negative slope of the I.F. response curve (530 KHz ±75 KHz).

VII. LABORATORY PROCEDURES AND RESULTS

Whenever an engineering idea is theorized, laboratory experimentation is generally accepted as proof of the validity or non-validity of such an idea. In this transition from an idea to experimental display, all too often modifications and/or complete changes are required of the original idea in order to complete the experiment with usable results. As will be seen, the work described in this paper is no exception to the above statement.

The initial approach to laboratory demonstration was congruent with the theory presented in the preceding chapters. The following is a summary of the laboratory procedures and results:

FM Signal Source

An FM/AM receiver, in the FM mode, was used as the FM signal source. Tapping of the FM I.F. signal (10.7 MHz ±75 KHz) was accomplished as shown in Figure 26. The following are the problems encountered and the solutions to those problems:

Problem - How could the tube for I.F. signal amplification be tapped without shorting the plate to ground?

Solution - Two resistors as shown in Figure 26 allow both high resistance to ground but low resistance for FM signal tapping.

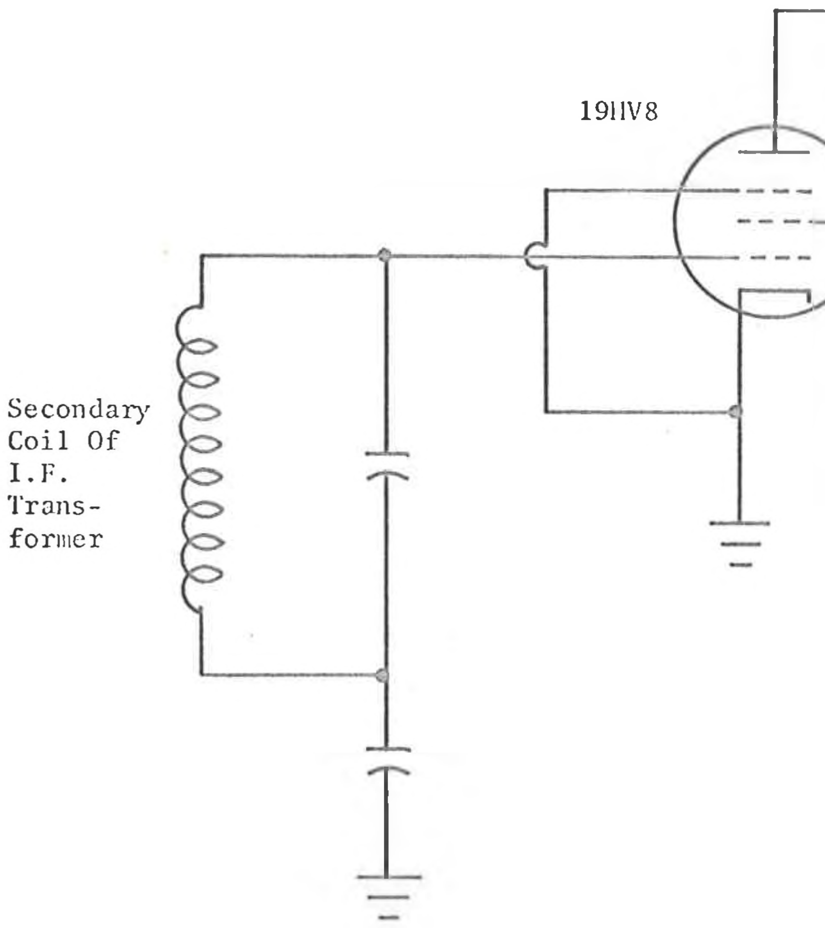
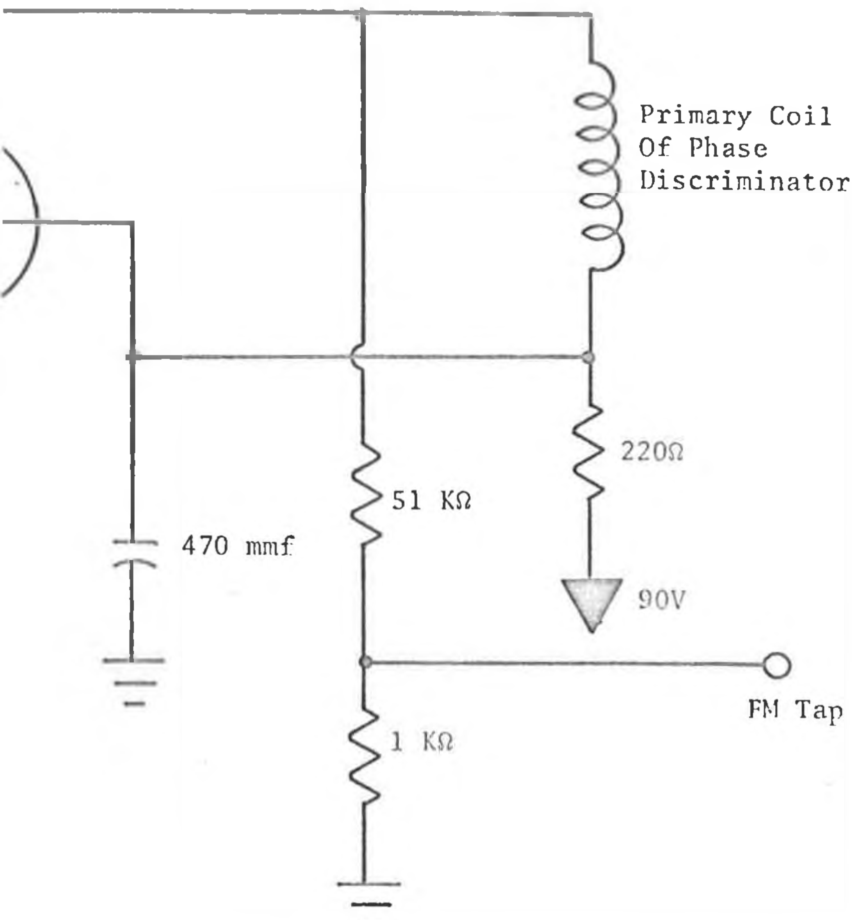


Figure 26 - FM


Primary Coil
Of Phase
Discriminator
220Ω
51 KΩ
470 mmf
90V
FM Tap
1 KΩ

M Signal Tap

Problem - Signal level, as tapped, was only 100 mv.

Solution - Commercial RF amplifier with 20 db and 40 db of gain.

Mixer

The mixer circuit was first evaluated with two constant amplitude signal generators. Parallel "T" matching networks, as described in Chapter IV, were used at the output of the signal generators to be consistent with the design requirements of the mixer. This requirement is for both inputs to have an impedance of 100Ω. The desired output was obtained, as displayed by an oscilloscope. Readily apparent were the original signals (undistinquishable from each other) and the difference frequency signal. No serious problems were encountered with the mixer.

Difference Filter

Data was taken on the difference filter (bandpass filter) to obtain its response curve characteristics. This data is available in Chapter VI. No serious problems were encountered with the difference filter. As described in Chapter VI, the filter is acceptable if the negative slope of the AM I.F. response curve is used for FM to FM-AM conversion.

Mixer - Filter Combination

The mixer and difference filter were combined and their resultant output observed on an oscilloscope. The output appeared as shown in Figure 27. As is apparent from Figure 27, the difference filter was not performing satisfactorily in attenuating the 10.7 MHz ±75 KHz FM I.F. signal. This was not considered critical, however, due to the filtering action of the AM receiver I.F. circuitry.

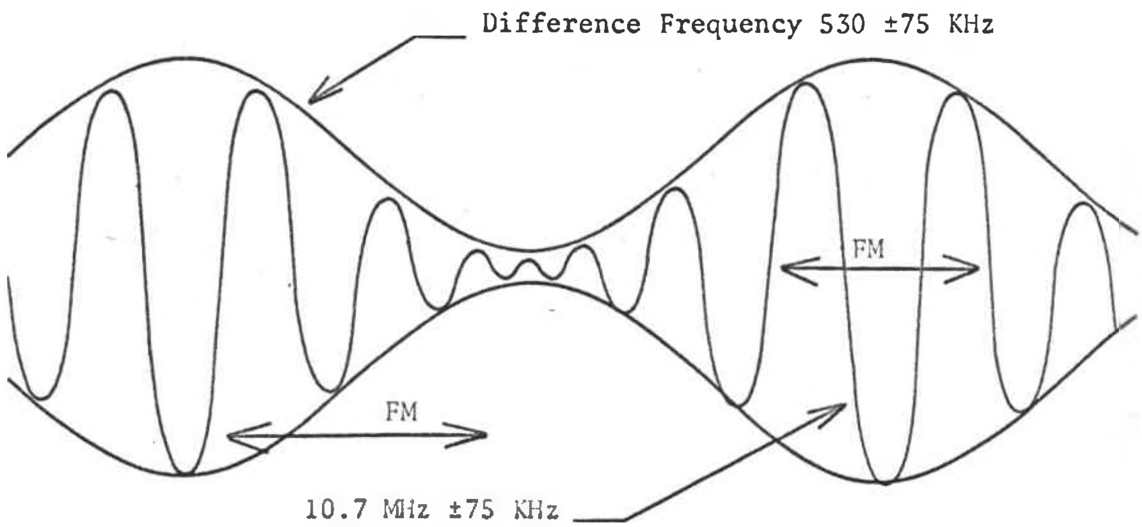


Figure 27 - Output Signal Of Mixer - Filter Combination

AM Receiver

The AM receiver circuitry was now approached for possible location for FM signal insertion (now at 530 KHz ±75 KHz). As shown in Figure 28, the AM receiver contained two I.F. transformer circuits (labeled #2 and #3). Initially, the intent was to insert the signal

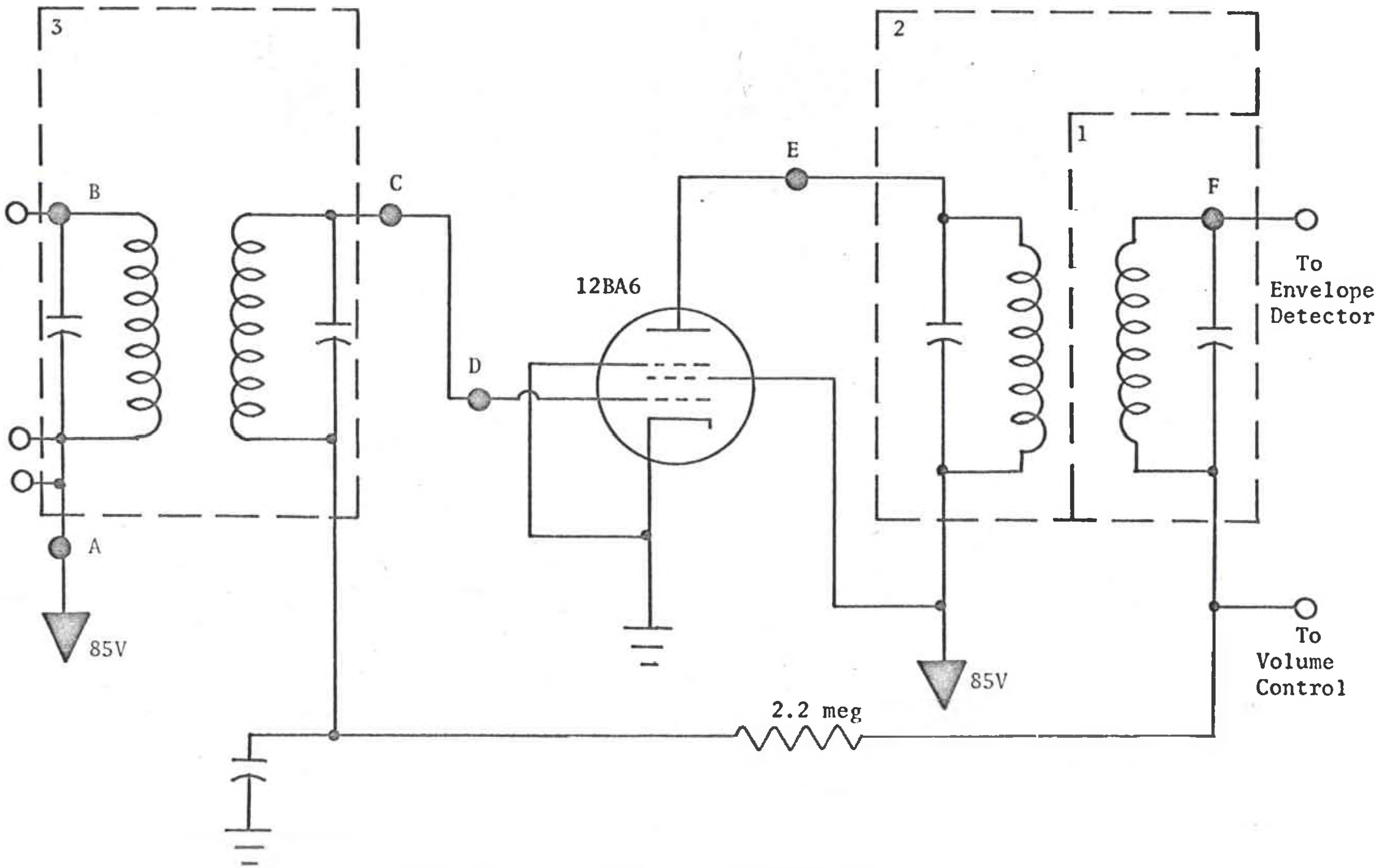


Figure 28 - AM Receiver - FM Insertion Point

at point F in tank circuit #1. At point E a switch was placed in order to turn the AM signal off when an FM signal was applied.

Integrated System

The system was now connected in its entirety. Before turning the system on, however, a common ground had to be established. The FM and AM radios wall plugs were two pronged, while the local oscillator and measuring instruments were three pronged. Three-to-two prong adapters were obtained. By connecting the grounds of each circuit, one at a time with a VOM to measure compatibility, common grounding was achieved. The following are the problems encountered in obtaining a workable system and the solutions to those problems:

Problem - After hook up and turn on of all systems, no sound was heard on the AM speaker.

Solution - Adjust voltage level of local oscillator and also tune local oscillator. This approach had negative results.

Solution - Check output signal of filter just prior to insertion in the AM radio. Oscilloscope showed that the signal was proper.

Solution - Check response curve of tank circuit #1. This result is shown in Figure 29. At this point consideration was given to two points:

1. Response curve showed that conversion could not take place at 530 KHz.

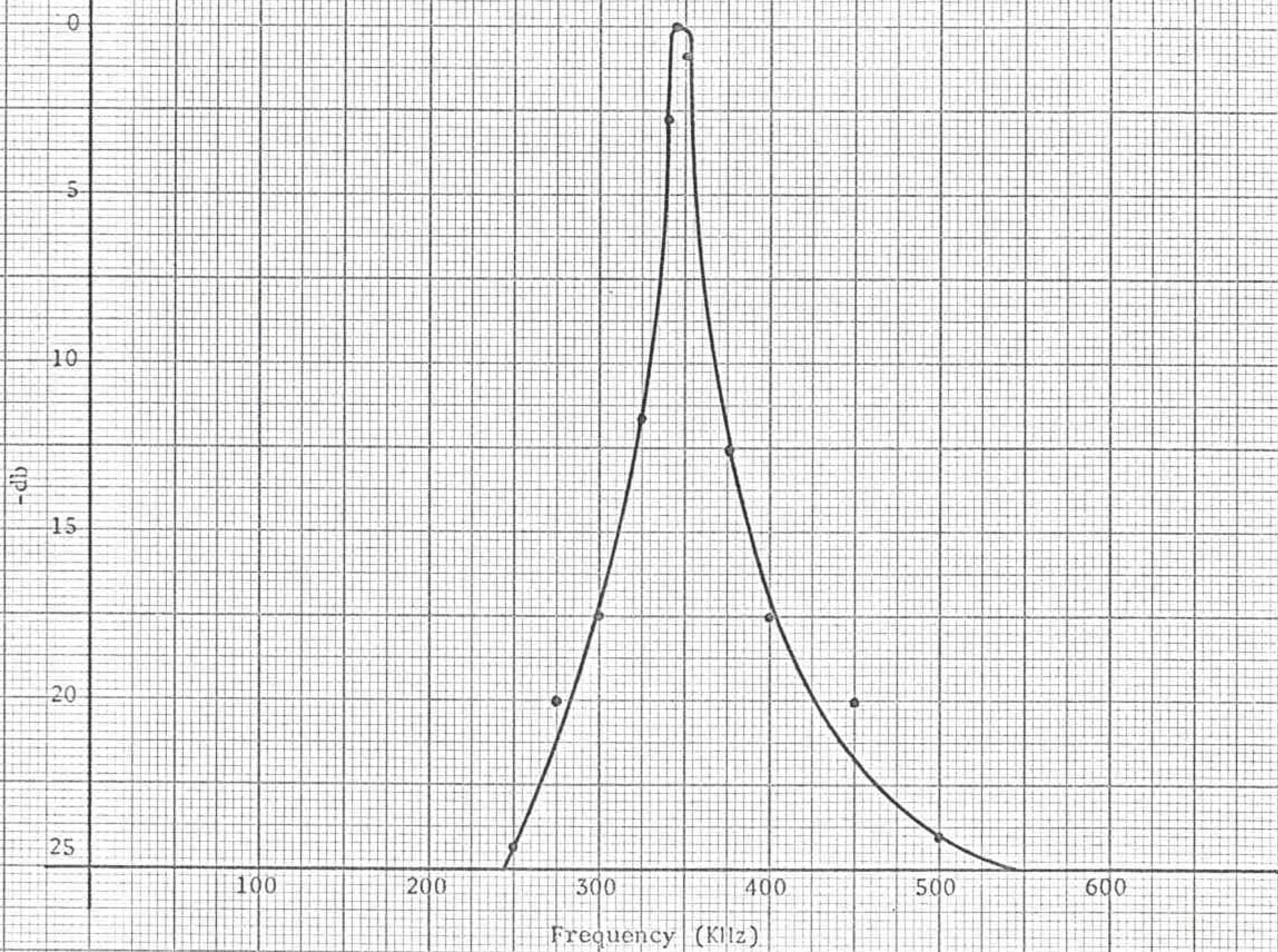


Figure 29 - Response Curve - Tank Circuit #1

2. Low impedance of the difference filter could destroy the "Q" of tank circuit #1.

Solution (reference Figure 28) - Insert FM signal at the grid of the I.F. amplifier tube (point "D"). Place on/off switches at points "A", "B" and "C". The signal was now applied with no positive results.

Solution - Excessive attenuation of the signal between FM and AM radios was next considered. Since the difference filter contained at least 20 db of attenuation, it was removed (keeping in mind that the AM radio I.F. tank circuit #2 would only respond to the 530 KHz ±75 KHz signal from the mixer). No positive results were reached.

Solution - Additional attenuation was taken from the circuitry with the removal of the "T" networks between the local oscillator-mixer combination and FM radio-mixer combination. The attenuation of the mixer, as calculated in Chapter V, would be changed by not keeping the signal inputs at the same impedance. However, the difference in attenuation by taking the "T" networks out was successful in permitting the system to operate properly.

The system operated as expected, with some distortion in the output signal as heard on the AM speaker. Detuning of I.F. transformer circuit #2 was now in order. A level was found where maximum signal and least distortion were reached. This was only accomplished after varying the local oscillator frequency from the original 11.23 MHz to 11.10 MHz. The response curve of the detuned transformer circuit (#2) is shown in Figure 30. It is obvious from this figure why the signal was best with the local oscillator frequency at 11.10 MHz. The difference between 11.10 MHz and 10.7 MHz is 400 KHz. This difference frequency is the center of the linear portion of the negative slope of the response curve.

A trace of the response curve of transformer circuit #3 was run and is shown in Figure 31. From this curve it appears that transformer circuits #2 and #3 were stagger tuned, each on either side of 455 KHz respectively to obtain the ±10 KHz bandwidth. It was originally thought that this stagger tuning was done by each transformer circuit individually.

After detuning, the distortion in the signal was still evident. To determine if the FM signal was overdriving the I.F. amplifier tube, the voltage level of the AM radio in normal operation was measured at point "D". It was found to be approximately 70 mv. The FM signal into this point was also measured and found to be 15 mv. Therefore it was concluded that no overdriving of the I.F. amplifier tube was being done and that this was not the cause of the distortion on the signal.

It was concluded that the width of the linear portion of the response curve in Figure 30 is not sufficient for the ±75 KHz deviations in the FM signal and was cause for most of the distortion in the signal. Of course noise and distortion can and probably were introduced in the transfer of the signal from the FM radio to the

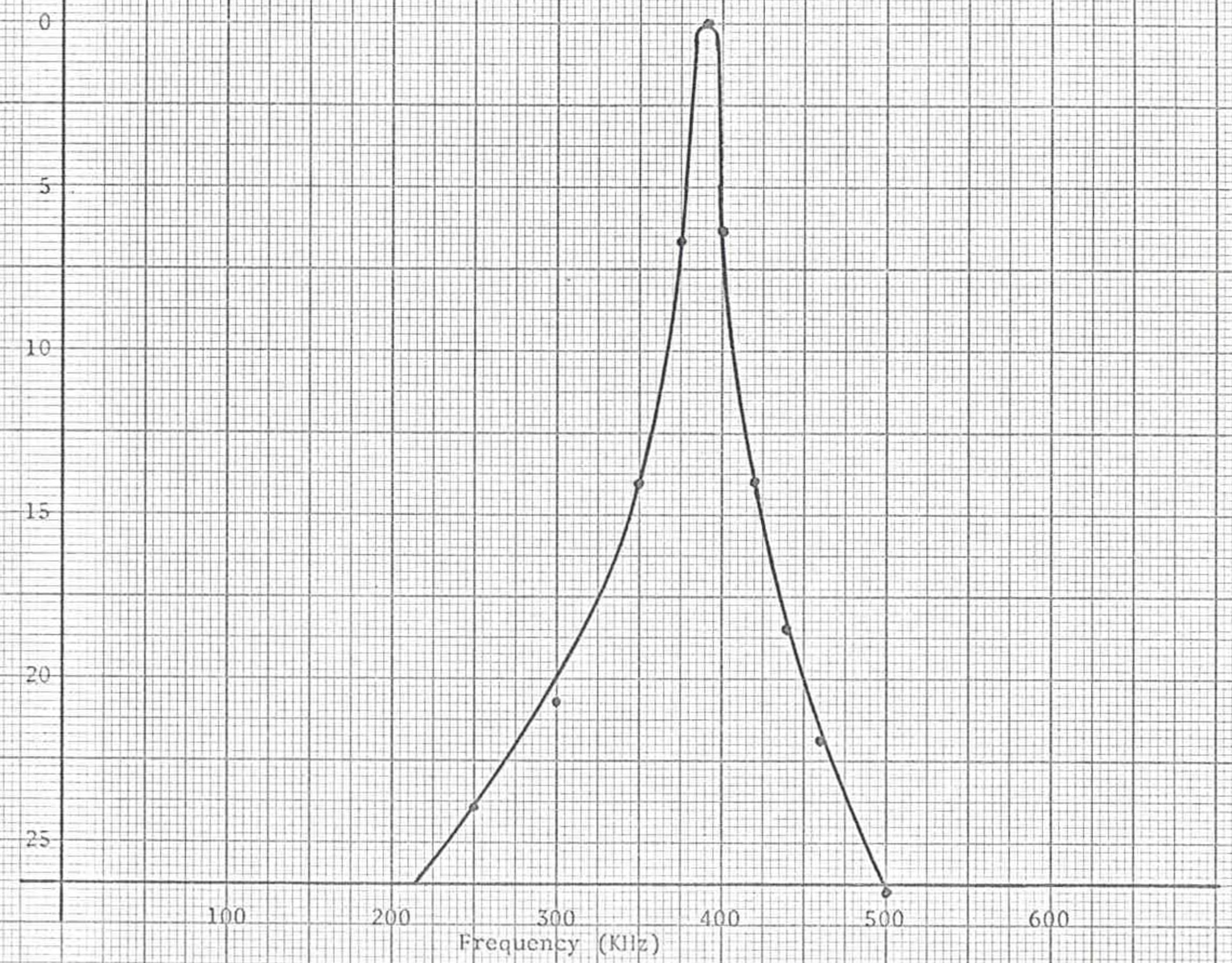


Figure 30 - Detuned Response Curve - Transformer Circuit #2

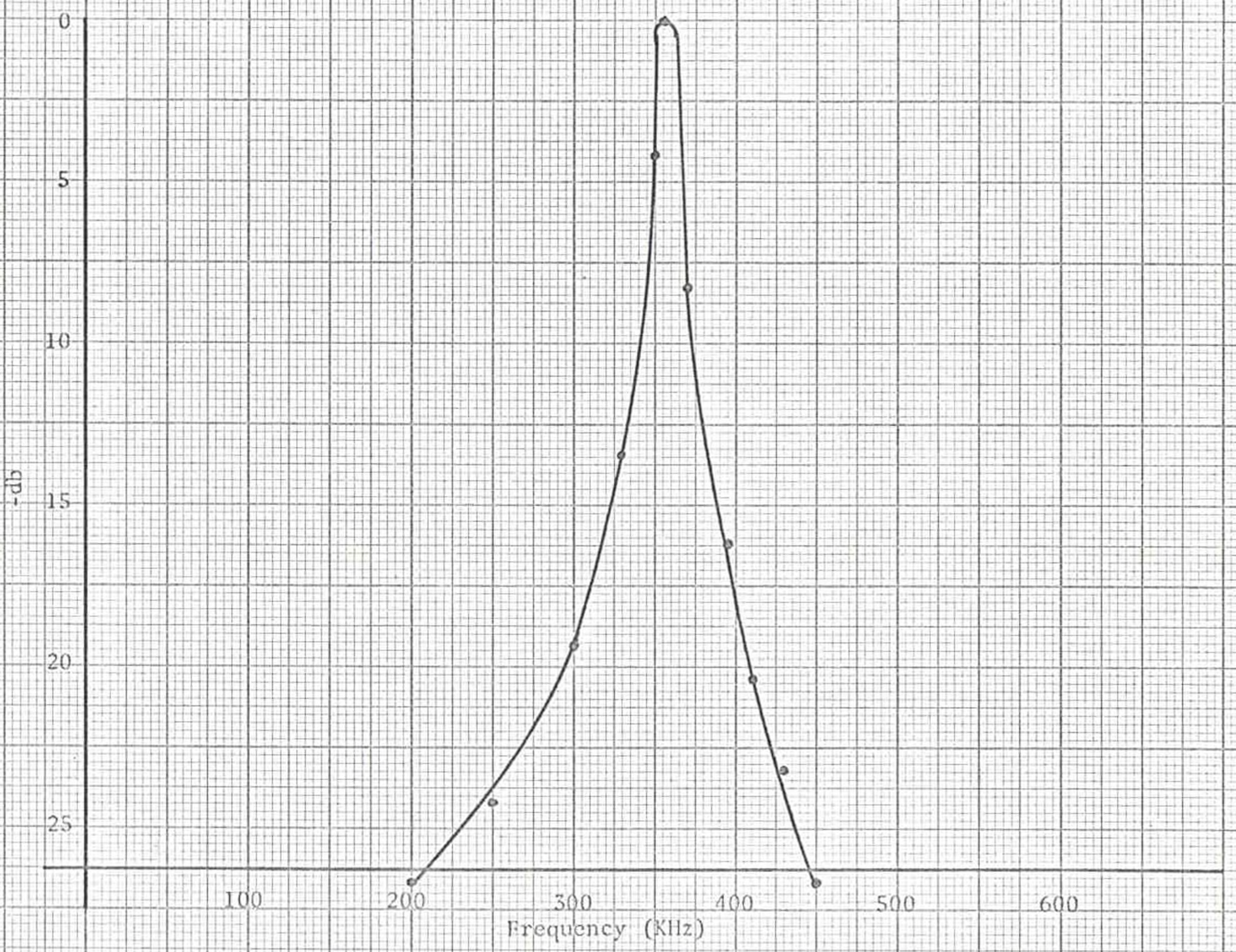


Figure 31 - Response Curve - Transformer Circuit #3

AM radio by the integration circuitry. However, the signal was easily recognizable as the FM station signal. The distortion noticed in the signal was similar to the distortion noticed when any radio is tuned slightly off frequency.

VIII. SUMMARY AND CONCLUSIONS

The implementation of detection of commercial radio FM and AM signals by a single detection device was proven to be feasible. Integration circuitry was developed in order to obtain the desired results. These results will now be applied in order to formulate application of an FM-AM detection device (AM I.F. response curve with associated envelope detector circuitry) to current FM/AM radios. Table 1 of Chapter III will be referenced in support of slope detection over other means of FM detection referenced.

As was expected, some distortion of the FM signal was audible after detection on the AM receiver circuitry. This was due primarily to the poor linearity of the detuned AM I.F. response curve. On the linear portion of this curve only an FM bandwidth of 30 KHz to 70 KHz could be realized with any degree of linearity. It can be concluded that the AM circuitry had the capability of FM detection but not with a resultant audio signal fidelity that is normally associated with FM receivers. This problem could be resolved by redesign of the AM I.F. transformer circuitry to yield a response curve similar to that shown in Figure 32. This curve could probably be realized with a tuned transformer circuit similar to the AM I.F. transformer circuit or a bandpass filter with skirts similar to the difference (bandpass) filter developed in Chapter VI. However, in order to reduce undesired responses outside of the 455 KHz ±10 KHz bandwidth,

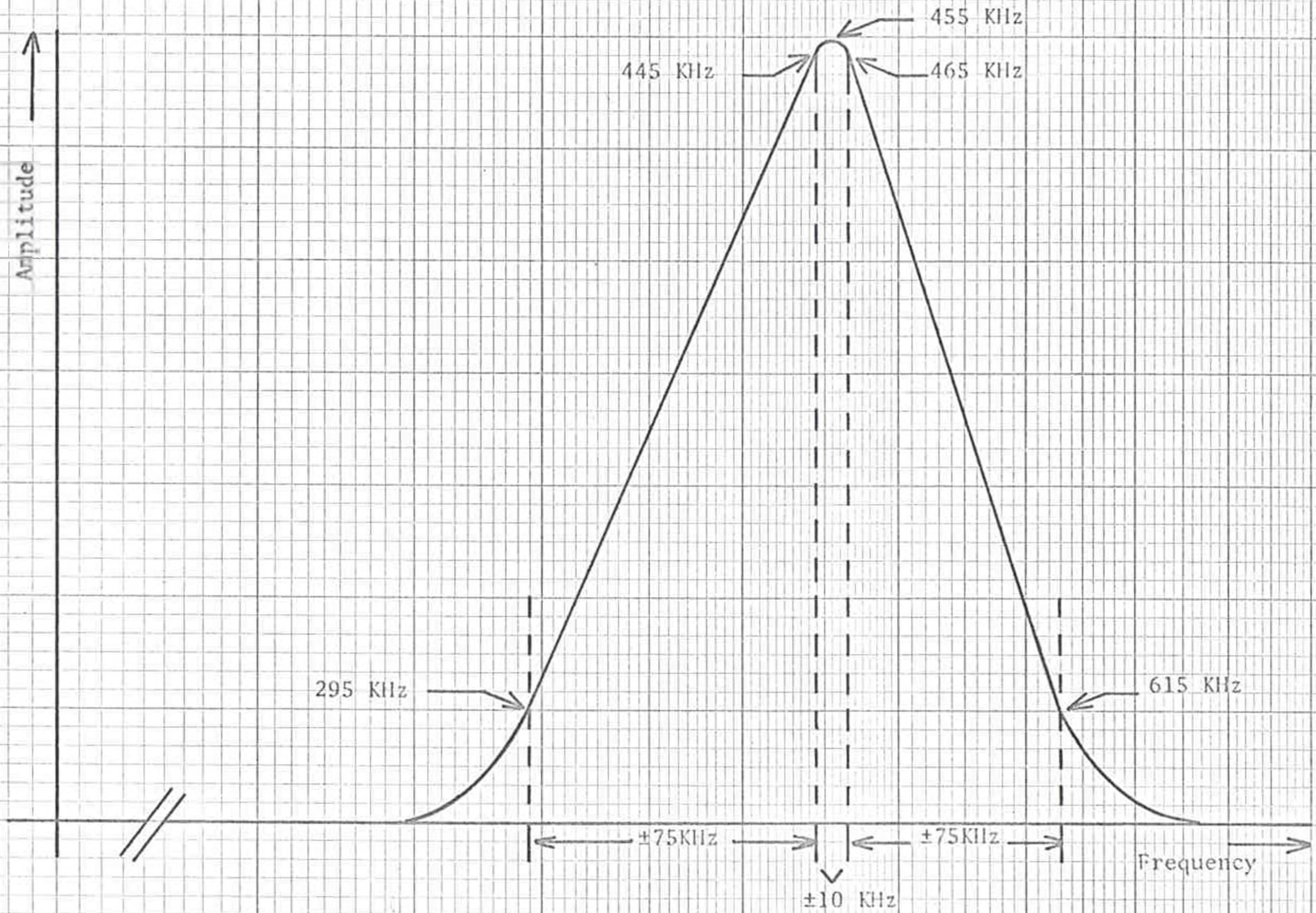


Figure 32 - Required AM I.F. Response Curve

the AM input signal would have to be of a very low level. This is because of the wide bandwidth associated with the response curve below the -3 db points.

Double conversion of the FM signal, as performed in this paper, would not be necessary. This is based on the signal fidelity established by current FM radios, of the type used in this paper, that do not incorporate double conversion techniques. Single conversion could be made from the rf signal to an I.F. frequency of 370 KHz or 540 KHz, depending on the design of the AM I.F. transformer (reference Figure 32).

The results of this paper have shown that the difference filter is not required. Any RFI problems that it might have solved were not readily apparent. The RFI problems that were encountered were not due to undesired signals generated by the mixer, but rather to long connector cabling and inadequacies of breadboard type construction.

Matching networks were a considerable problem in this paper. The attenuation offered to the system by these networks proved intolerable. The low VSWR and maximum signal transfer they offered the system did not compensate for the attenuation they provided. Matching networks were removed from the L.O. - mixer combination, the FM I.F. signal - mixer combination, and the mixer - AM radio combination resulting in total system operation without noticeable degradation.

In referring to Table 1, several points are to be brought out in favor of the slope detector (AM I.F. transformer and associated envelope detector). Symmetry balance, phasing between primary and secondary, and diode arrangement are not applicable to the slope detector but are crucial (except for phasing in the frequency discriminator) to present FM detection devices. The number of tuned circuits is limited to one (possibly two for a stagger-tuned type transformer) in a slope detector and insures the possibility of less chances of inadequate tuning of circuitry. Poor linearity appears to be the only relatively bad feature of the slope detector. This was brought out quite noticeably in the results of Chapter VII (distortion of the audio signal). This could be corrected with the design of a circuit having a response curve similar to that of Figure 32.

From the results of Chapter VII and the discussions thus far, it can be concluded that FM/AM radios with a singular detection device are feasible if modifications are made as follows:

- Eliminate from (present) FM/AM radios -

1. FM detection device
2. AM I.F. transformer
3. Local oscillator
4. FM I.F. transformer (10.7 MHz)

- Incorporate into (new) FM/AM radio -

1. Circuit to yield a response curve similar to Figure 32

2. Local oscillator

3. FM I.F. transformer to accommodate new I.F. frequency

As can be seen, more circuitry is eliminated than is incorporated in the FM/AM radio. The result is less circuitry for an FM/AM radio employing a single detection device. The resultant fidelity should be comparable to present FM radios of the type used in this paper (G.E. models T225A, T235A, and T236A). This statement is made making note of the slightly distorted audio signal developed in this approach. If such good quality in an audible signal could be detected with the poor linearity of the AM I.F. transformer used in this paper, it is anticipated that good fidelity with redesign, as noted in this chapter, can be achieved.

In conclusion, this paper has shown the following: 1) Feasibility of single detection of commercial FM and AM signals; 2) Circuit requirements to perform single detection; and 3) Benefits of single detection to present FM/AM radios.

BIBLIOGRAPHY

1. Carlson, A. B. Communication Systems - An Introduction To Signals And Noise In Electrical Communication. New York: McGraw-Hill Book Co., Inc., 1968.

2. Television - How It Works. New York: John F. Rider Publisher, Inc., 1948.

3. Rider, J. F. and Uslan, S. D. FM Transmission And Reception. New York: John F. Rider Publisher, Inc., 1948.

4. Radiotron Designer's Handbook. Australia: Amalgamated Wireless Valve Company Pty. Ltd., 1952.

5. Stewart, J. L. Circuit Theory and Design. New York: John Wiley and Sons, Inc., 1956.

6. Nomograph: Reduction Of VSWR As A Function Of Attenuation. New York: Polytechnic Research And Development Co., Inc.